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THE SINOTYPE—A MACHINE FOR THE COMPOSITION OF CHINESE FROM A KEYBOARD*

BY

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INTRODUCTION

The sharing of knowledge and skills on a world-wide scale is one of the proudest achievements of man. Printed matter without question is used for most of the transmission and storage of human knowledge. The world's enormous publishing industry and its millions of collections—public and private—of printed material bear witness to man's eager use of this medium. But not all men have been equally well served by printing.

Although the Chinese are said to have developed the first form of type,[2] the engraved wood blocks of about 700 A.D., printing in the modern sense arose from the invention of movable type by Gutenberg in 1440. Progress in Western printing then became swifter and swifter. The processes in use at first were manual, and the Chinese printer was at no significant disadvantage technically. During the next two centuries, however, changes in Western printing were revolutionary, and the most important of the new developments could not be used by the Chinese printer.

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* The preliminary phases of this work were performed at the Graphic Arts Research Foundation, Inc., Cambridge, Massachusetts, under a grant from the Carnegie Corporation of New York. This program essentially determined the feasibility of the proposed method. The actual development and construction of an operative machine were performed at the Foundation under a Government Contract supervised by the Quartermaster Corps and jointly funded by the United States Army and Air Force.

[1] Professor of Electrical Engineering, Massachusetts Institute of Technology, and Director of Research, Graphic Arts Research Foundation, Inc., Cambridge, Mass.

[2] CEDRIC LARSON, "The Story of Wood Type," *Am. Printer and Lithographer*, Vol. 137, p. 28 (1956).

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This was the impact of the change from hand composition to keyboard-controlled machine composition. Mergenthaler's Linotype was commercially successful by about 1890, and Lanston's Monotype by about 1895. These key inventions brought new economies to printing and were foundation elements of the Western printing and publishing structure. But they served basically the languages in which words are written as single-line sequences of alphabetic symbols.

This paper describes a new approach to the problem of composing written Chinese. The material to be composed enters the machine by way of a typewriter keyboard; the end product is a photographic film carrying images of the Chinese characters selected. Standard commercial processes and equipment are available for going through the remaining steps between the film and the final printed page.

FUNDAMENTALS OF THE PROBLEM

There have been a number of attempts to solve the problem of composing Chinese writing on a keyboard. These efforts have been devoted primarily to the development of a practicable typewriter. The successful development of a photocomposing machine[3] with an extraordinarily large "built-in" array of type styles and sizes soon raised the question of whether by extension and modification of the photographic techniques it might be possible to mechanize the composition of more of the world's writing forms. Technically the problem was one of unquestionable challenge, but the challenge was enormously enhanced by the sheer magnitude of the consequences of a practicable solution, in terms of the enlightenment and social enrichment of millions of humans.

V.2
195

Several aspects of this problem are not particularly obvious. These will be reviewed briefly because they have the effect of applying strong constraints on the machine's design.

A first consideration is the quality of the finished product. The Chinese—and, indeed, many of the Asian peoples—have a highly developed taste for good calligraphy. It is doubtful that a machine output of quality inferior to that obtained by manual typesetting would be acceptable. This consideration effectively requires rejection of any design approach based upon the idea of constructing a character on film by the superposition, in multiple exposures, of a set of more elementary symbols. It is true that complete characters are formed by assembling them from a limited number of basic strokes, but within the area occupied by a character a given stroke can appear almost anywhere and with a wide variation in its dimensions. To assemble characters in this manner, by machine, would require drastic and arbitrary limitation of the flexibility in stroke size and position which is inherent to Chinese writing. Previous attempts using this method produced results which were completely unacceptable.

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[3] W. W. GARTH, JR., "Higonnet-Moyroud Photographic Type Composing Machine," *Penrose Annual*, Vol. 45, pp. 95–97 (1951).

S. H. CALDWELL, "Technical Features of the Higonnet-Moyroud Photocomposing Machine," *ibid.*, Vol. 46, pp. 119–123 (1952).

S. J. PAINE, "Photon." Two articles under this title are published in *Printing Equipment Engineer*, in March 1954 and in October 1956.

If a desired character cannot be "built up," it must be available within the machine *in toto*. Moreover, it must be possible for the machine's operator to bring any character into position for photography. Just how an operator controls the machine is the next major consideration.

A number of earlier workers devised typewriters in which the vocabulary of characters was arrayed on a cylindrical matrix. At the keyboard the operator depressed keys which, in effect, specified the cylindrical coordinates of a desired character. In subsequent operation the matrix cylinder received a combination of shift and rotation orders which brought the selected character into the printing position.

This is the most elementary approach to the selection problem and it reveals the major difficulty that has led to the failure of all attempts to compose Chinese from a keyboard. *In order to select a character by this method the operator must know a special code description for that character.* He must either memorize the code, or he must look it up in a reference list. Even for the machine to be described, with a vocabulary of fewer than 2400 characters, this would require a prodigious program of special training. In terms of a more realistic vocabulary size—say 6000 to 8000 characters—it is hardly likely that any adequate proportion of a Chinese-speaking population could ever expect to qualify as operators. More subtle approaches than the cylindrical coordinate code scheme require somewhat less special training, but essentially they fail to solve the problem of making the keyboard one which *most* Chinese-speaking people can master.

In contrast, the operator of a keyboard for composing or typing in English, French, German, or any other language written as sequences of alphabetic symbols, must know primarily how to read the words and, preferably, how to spell them. These are skills he acquires as part of his elementary education and he needs no further special training in them.

What kind of writing skill does the Chinese student acquire in the course of his elementary education? Strangely enough, it turns out that he learns to write ideographic characters very much as his alphabetic brother learns to write words.[4]

Chinese has an "alphabet," in the sense that all Chinese characters are written by selecting strokes from a relatively small number (21) of basic strokes.

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[4] Here I must point out that I have no personal knowledge of written or spoken Chinese. The ideas developed here were first brought out in a conversation with a former student, Mr. F. F. Lee, and were subsequently verified and amplified by Prof. L. S. Yang, of the Department of Far Eastern Languages, Harvard University. (S.H.C.)

Chinese has a "spelling," in the sense that the sequence of strokes used in writing a given character is invariant. There is nothing whimsical about the process of setting down the strokes that comprise a Chinese character. Every Chinese learns to write a character by using exactly the same strokes in exactly the same sequence.

Quite a bit more than this is needed, but these two established facts—the existence of a Chinese "alphabet," and the existence of a Chinese "spelling"—make possible a keyboard for composing Chinese which can be operated by anyone who has learned to write Chinese. The machine must still operate under the handicap of requiring a code to describe the location of a character in a matrix, but the code requires no special learning on the part of the operator; it is derived from the keyboard equivalent of the stroke sequence the *operator learned in school.*

In highly simplified form, Fig. 1 illustrates the essentials of the system. At the left the operator furnishes to a keyboard the sequence of strokes which "spells" the desired character. Within the keyboard circuits each stroke is converted to its own binary code. The digits of the individual stroke codes are then transmitted to an accumulator circuit where the individual stroke codes are combined to form a larger code which describes the desired character. Finally, in the Character Selector the character code is converted into signals which describe the horizontal and vertical coordinates of the character in a rectangular photographic matrix.

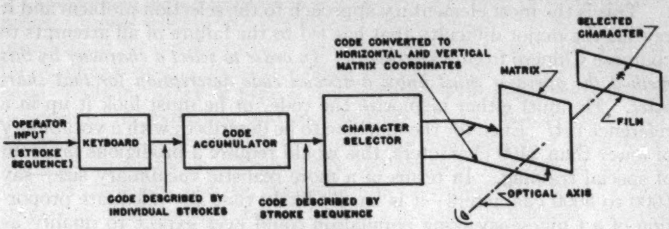
SELECTED CHARACTER
CODE CONVERTED TO HORIZONTAL AND VERTICAL MATRIX COORDINATES
MATRIX
FILM
OPERATOR INPUT
(STROKE SEQUENCE)
KEYBOARD
CODE ACCUMULATOR
CHARACTER SELECTOR
CODE DESCRIBED BY INDIVIDUAL STROKES
CODE DESCRIBED BY STROKE SEQUENCE
OPTICAL AXIS

FIG. 1.

CHINESE STROKES, STROKE SEQUENCES, AND AMBIGUITIES

The group of 21 basic strokes shown in Fig. 2 are those adopted for use on the keyboard.[5] Each stroke is identified by a letter of the Latin alphabet appearing in the first column and the stroke itself is shown in the second column. In the third column is shown the frequency of appearance of the stroke in representative samples of Chinese writing. The *B*, *D*, and *G* strokes are shown in long and short forms because in the first selection of strokes to be used these pairs were considered, and identified, as separate strokes. It was soon found, however, that in many characters it is difficult for even well-educated Chinese to be sure whether a given stroke is long or short. The difficulty was resolved by eliminating all distinctions between "long" and "short." Likewise, the three forms of the *E* stroke and the two forms of the *S* stroke are disregarded in determining stroke sequences.

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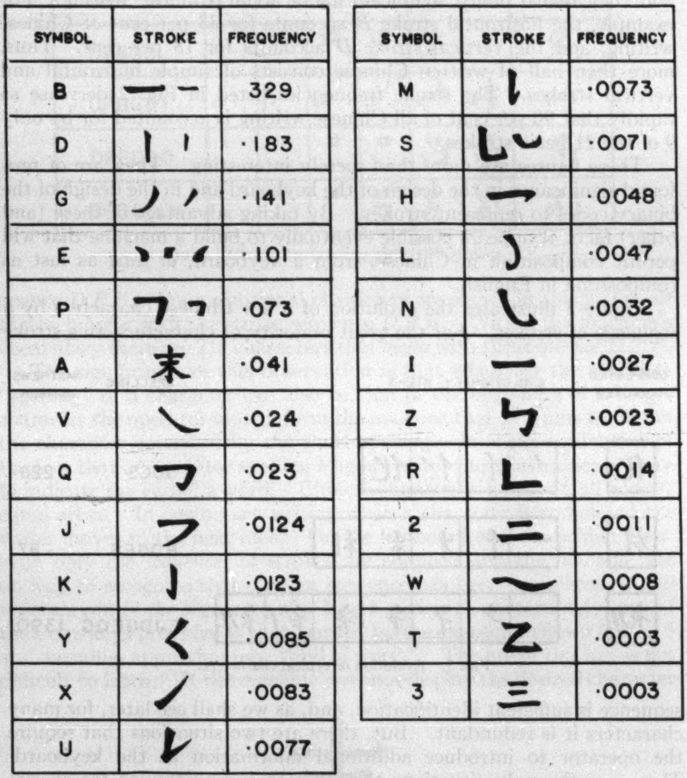
[5] This selection was made by Prof. L. S. Yang. He also took the responsibility for supervising and verifying the work of a group of Chinese analysts who established the correct stroke sequences for the 2333 characters contained in the vocabulary of the machine.



SYMBOL	STROKE	FREQUENCY
B		329
D		·183
G		·141
E		·101
P		·073
A	末	·041
V		·024
Q		·023
J		·0124
K		·0123
Y		·0085
X		·0083
U		·0077

SYMBOL	STROKE	FREQUENCY
M		·0073
S		·0071
H		·0048
L		·0047
N		·0032
I		·0027
Z		·0023
R		·0014
2		·0011
W		·0008
T		·0003
3		·0003

FIG. 2. Basic strokes arranged in order of decreasing frequency.

An obvious advantage of the use of letters of the alphabet to identify strokes is that a sequence of strokes can be rewritten as a sequence of letters. Then the sequences of letters—each representing a Chinese character—can be transferred to punched cards, and the entire vocabulary can be manipulated and studied by high-speed computing machinery.

From such studies the frequency figures given in the third column of Fig. 2 were obtained. These figures have never before been available and they reveal many significant facts about Chinese writing. For example, the horizontal stroke *B* accounts for 33 per cent of Chinese writing, and the vertical stroke *D* accounts for 18 per cent. Thus, more than half of written Chinese consists of simple horizontal and vertical strokes. The stroke frequencies listed in Fig. 2 decrease so rapidly that 90 per cent of all Chinese writing is accounted for by only 9 of the 21 basic strokes.

These figures are more than merely interesting. They are of profound significance in the design of the keyboard and in the design of the binary codes to represent strokes. By taking advantage of these (and other) facts, it appears possible eventually to build a machine that will permit composition in Chinese, from a keyboard, *at least* as fast as composition in English.

Figure 3 illustrates the evolution of a few Chinese characters by a sequence of strokes. For the great majority of characters, this stroke sequence is sufficient identification, and, as we shall see later, for many characters it is redundant. But, there are two situations that require the operator to introduce additional information at the keyboard. These are the only situations that impose a requirement for special training of the operator, and neither is particularly onerous.

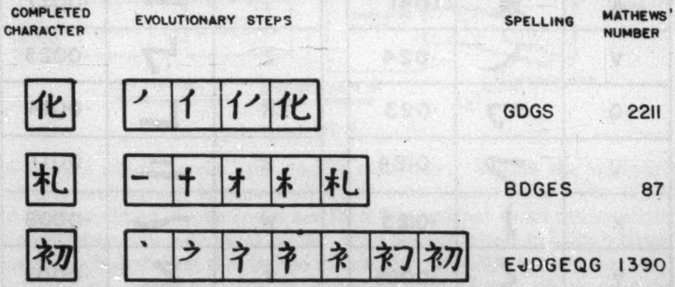


FIG. 3. Evolution of typical characters.

One of these situations has a close counterpart in English (and in other alphabetic languages). Consider the English words EVE, EVER, EVERY, EVERYONE and EVERYONE'S. Each of these words, except the last, is the beginning of the next word in the list. Similarly, in Chinese many stroke sequences can represent either complete words or the beginnings of longer words. In Fig. 4, the first row shows the evolution of the character for "mouth," derived from the stroke se-

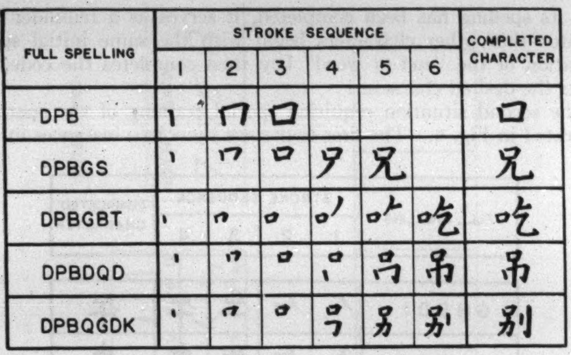

FULL SPELLING
STROKE SEQUENCE
1
2
3
4
5
6
COMPLETED CHARACTER
DPB
口
DPBGS
兄
DPBGBT
吃
DPBDQD
吊
DPBQGDK
别

FIG. 4. Characters starting with DPB strokes.

quence *D P B*. Four additional characters are shown in this figure, all of which *begin* with the stroke sequence *D P B*. Within the machine's vocabulary there are 215 characters that *begin* with the sequence *D P B*.

The significance of this observation is that whenever the complete "spelling" of a character can also be that of the beginning of a longer character the operator must inform the machine that he wants to obtain the character described by the short spelling. It is the equivalent of the fact that an operator spelling English words must introduce a space to indicate the end of a word. Chinese characters, however, all occupy equal areas. In customary writing when a character is completed the writer moves to the next area. On the keyboard of the machine, however, only the *sequences* of strokes are supplied and the machine has no way to recognize that a given sequence has been completed, *if that sequence can be the beginning of a longer sequence.* Accordingly, one of the extra keys provided is that marked by the character shown in Fig. 5 and meaning, approximately, "end of word." The use of this key is not difficult to learn. If the machine does not display the desired character

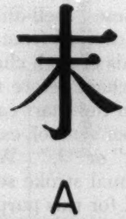


FIG. 5. "End of Word" character. This key appears in the right side of the home row of the keyboard.

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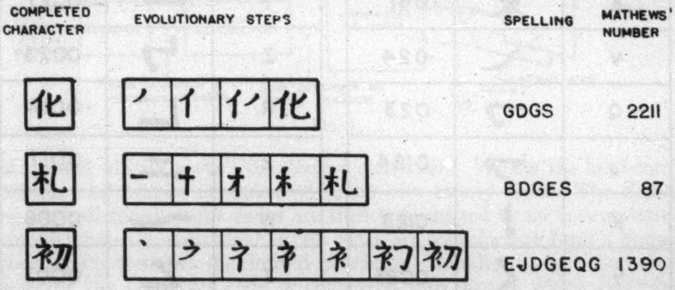

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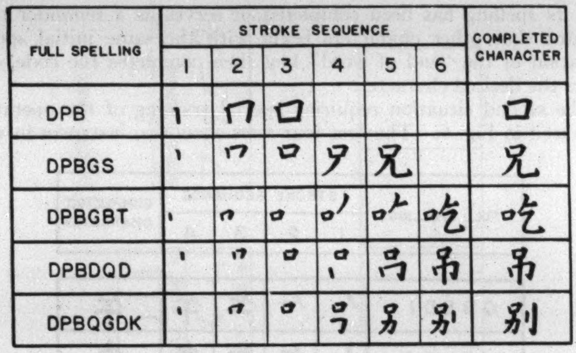

FULL SPELLING	STROKE SEQUENCE						COMPLETED CHARACTER
	1	2	3	4	5	6	
DPB	丨	𠃍	口				口
DPBGS	丨	𠃍	口		兄		兄
DPBGBT	丨	𠃍	口			吃	吃
DPBDQD	丨	𠃍	口			吊	吊
DPBQGDK	丨	𠃍	口				别

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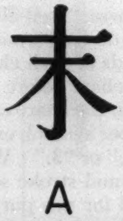

FIG. 5. "End of Word" character. This key appears in the right side of the home row of the keyboard.

after its spelling has been completed, it serves as a reminder to the operator that other characters begin with the same initial spelling. Actuation of the "end of word" key then completes the code which selects the desired character.

The second situation requiring special training of the operator is illustrated in Fig. 6. The first four rows show two instances in which a given stroke sequence leads to two different characters, and in the next three rows a single stroke sequence leads to three possible characters. There is no exact counterpart to this situation in English. Fortunately there are relatively few of these "spell-alike-look-different" characters in the vocabulary. Listings derived from punched-card machines disclose only 20 pairs and 4 triads of such characters. These ambiguities are resolved by mounting a chart before the operator to show all the characters thus involved. On the chart each of the ambiguous characters is associated with a number symbol, expressed in Chinese form, and standing for either "1," or "2," or "3." When the appropriate numerical suffix is added to the normal stroke sequence of the character, by means of extra keys provided for this purpose, the desired character is fully identified. The special training thus required involves slightly

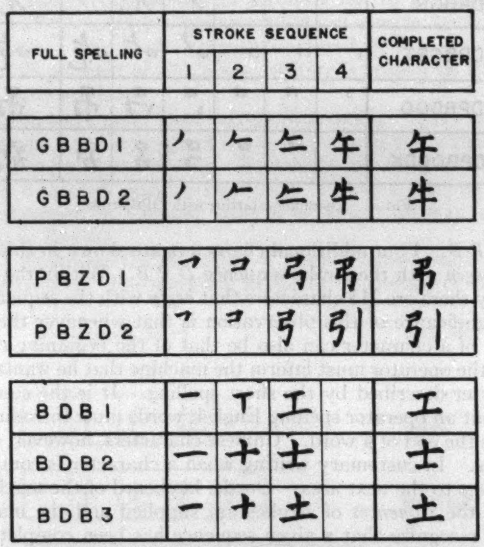

FIG. 6. Examples of identical stroke sequences leading to different characters.

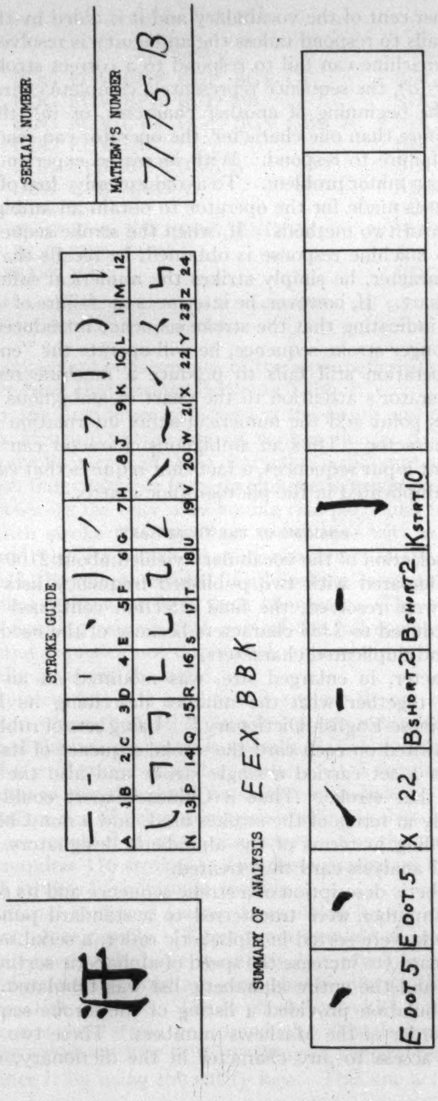
SERIAL NUMBER
MATHEW'S NUMBER
7175 B
STROKE GUIDE
A 1
B 2
C 3
D 4
E 5
F 6
G 7
H 8
J 9
K 10
L 11
M 12
N 13
P 14
Q 15
R 16
S 17
T 18
U 19
V 20
W 21
X 22
Y 23
Z 24
SUMMARY OF ANALYSIS
E E X B B K
E DOT 5
E DOT 5
X 22
B SHORT 2
B SHORT 2
K STRT 10

FIG. 7.

more than 2 per cent of the vocabulary and it is aided by the fact that the machine fails to respond unless the ambiguity is resolved.

Since the machine can fail to respond to a correct stroke sequence because either (*a*), the sequence represents a complete character which can also be the beginning of another character, or (*b*), the sequence can describe more than one character, the operator can readily be confused by the failure to respond. With increased experience this confusion becomes a minor problem. To avoid excessive loss of time, however, provision is made for the operator to obtain an ambiguous character by either of two methods. If, when the stroke sequence is completed and no machine response is obtained, he recalls that this is an ambiguous character, he simply strikes the numerical suffix key indicated on the chart. If, however, he interprets the failure of the machine to respond as indicating that the stroke sequence introduced is the beginning of a longer stroke sequence, he will operate the "end of word" key. This operation still fails to produce a machine response and directs the operator's attention to the chart of ambiguous characters. He can at this point add the numerical suffix information and obtain the desired character. Thus an ambiguous character can be selected by two different input sequences, a fact that requires that each of these characters be duplicated in the photographic matrix.

V.2
195

ANALYSIS OF THE VOCABULARY

An initial selection of the vocabulary yielded about 2100 characters. These were compared with two published frequency lists and, after discrepancies were resolved, the final selection contained 2337 characters, later reduced to 2333 characters because of the need to include punctuation and duplicated characters.

Each character, in enlarged size, was mounted on an individual analysis card, together with the number describing its location in Mathews' "Chinese-English Dictionary." Using sets of rubber stamps, the analysts printed on each card the stroke sequence of its character. Each stamp in a set carried a single stroke and also the alphabetic designator of that stroke. Thus a Chinese expert could verify an analysis directly in terms of the strokes used, and a non-Chinese could record the spelling in terms of the alphabetic designators. Figure 7 shows a typical analysis card thus treated.

Each alphabetic description of a stroke sequence and its corresponding Mathews' number were transferred to a standard punched card. After these cards were sorted in alphabetic order, a serial number was added to each card (to increase the speed of alphabetic sorting in future manipulation) and the entire alphabetic list was tabulated. Another sorting and tabulation provided a listing of the stroke sequences arranged in the order of the Mathews' numbers. These two lists made possible rapid access to any character in the dictionary, even by a non-Chinese.

TABLE I.

Mathews' Number	Full Spelling	Minimum Spelling
851	BDG EGV BDP BDP BGE GE	BDG EGV B
680	BDG EGV EPB BGD PB	BDG EGV E
4899A*	BDG EGV GVB DGE BGV GBB K	BDG EGV G
5552	BDG EGV UE	BDG EGV U
3201	BDG EPB BME BRG S	BDG EPB BME
3328	BDG EPB BMG V	BDG EPB BMG
87	BDG ES	BDG ES
411A*	BDG EYU EYU EBG ENG E	BDG EY
5890	BDG SEE EPW	BDG S
4593	BDG VA	BDG VA

* Two characters appear under Mathews' Numbers 4899 and 411. The letter A designates the first listed character, in each instance.

A more important consequence of the alphabetic listing can be seen in an extract from that listing, shown as Table I.

Consider the first four characters in the group and note that their spellings are identical for the first six strokes, that is, *BDG EGV*. But the seventh stroke in each of these characters is different and is sufficient to distinguish that character from its alphabetic neighbors. Since these four characters are the only ones having this particular initial spelling, at the seventh stroke their spellings are unique with respect to their neighbors and with respect to all other characters in the vocabulary.

In Table I, the column headed "Full Spelling" shows the sequence of all the strokes written to form each character. The column headed "Minimum Spelling" shows that part of the full spelling which is the shortest initial sequence not duplicated, as a whole or in part, by any alphabetically adjacent character.

It will be seen that this condition is apparently not satisfied by the last character, where the final *A* "stroke" seems redundant. However, the spelling of the last character is actually *BDGV* and the *A* stands for the "end of word" stroke described earlier. It is required because the next character in the alphabetic list *begins* with *BDGV*.

The consequence of using minimum spelling is that fewer keyboard operations are required to select characters. For the sample shown in Table I, it requires 116 strokes to find these characters by full spelling, and only 65 strokes by minimum spelling.

An additional keyboard feature is available for the operator to use in composing more rapidly. There are a number of groups of strokes which do not necessarily have meanings, but which occur often in the spelling of characters. They are somewhat similar to English syllables such as *-ing*, *-tion*, or *-ous*. The keyboard provides for twenty of the most frequent of these stroke groups, which will be designated as *entities*. If there is an entity present in the spelling of a character, the operator may introduce it by using the entity key. This one action introduces the complete stroke sequence contained in the entity just as though the individual stroke keys had been used. Actually, it is likely that an unskilled operator will use the stroke keys until he learns to recognize the opportunity to save time by using entity keys. Figure 8 shows the entities used on the keyboard. The way they appear in characters is illustrated in Fig. 9.

The influence of the entities in improving the speed of composition may be seen by referring again to Table I. The sequence *BDGE* is one

V.2
195

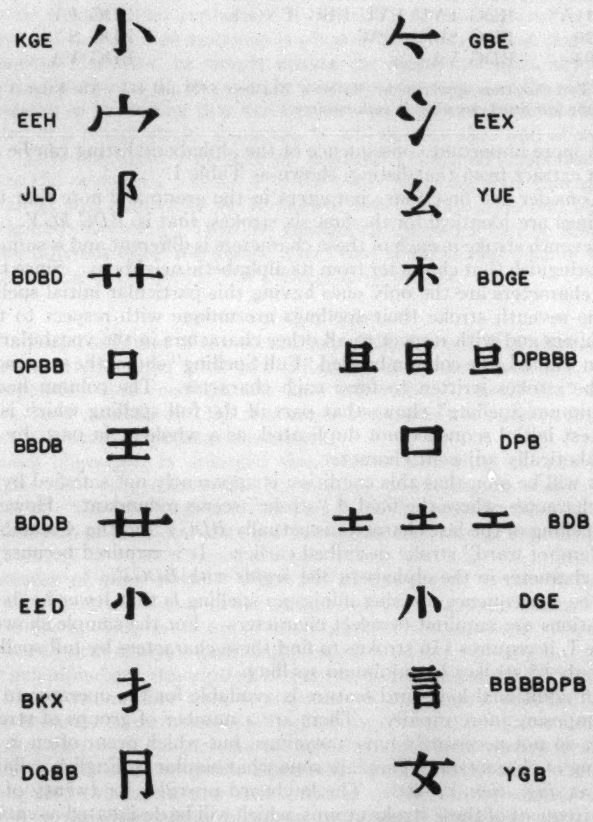
KGE
GBE
EEH
EEX
JLD
YUE
BDBD
BDGE
DPBB
DPBBB
BBDB
DPB
BDDB
BDB
EED
DGE
BKX
BBBBDPB
DQBB
YGB
UPPER CASE
LOWER CASE

FIG. 8. Keyboard entities.

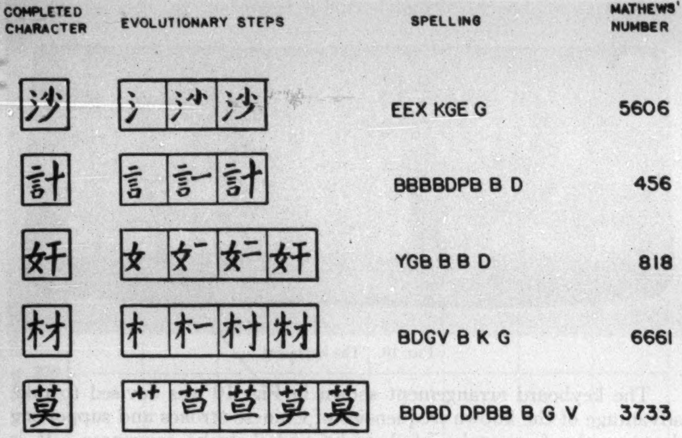

FIG. 9. Examples of use of entities in characters.

of the frequent entities. If the key for this entity is used in the eight characters of the sample where it is applicable, the number of keyboard operations is reduced from 116 to 41, a ratio of almost 3:1.

THE KEYBOARD AND ITS OUTPUT CODES

In Fig. 2 the frequencies associated with individual strokes are tabulated. These frequency values are those derived from the full spelling of the complete vocabulary, with no weighting of the individual characters. Samplings were also made of the frequency distribution in representative Chinese prose, in which character frequencies might influence the result. In the limited samples that necessarily had to be used, the frequency shifts found were so small that they were considered negligible. Consequently, the stroke frequencies used are those found in a message which contains each character of the vocabulary exactly once.[6]

The frequencies of occurrence of the individual strokes influence the machine design in two important ways. First, the placement of the strokes on the keyboard is related to the frequencies of the strokes, and to the sequences of strokes.[7] Second, by taking stroke frequency into account, the character description can be encoded with minimum, or nearly minimum redundancy. This type of coding makes it possible to design selection equipment of minimum size.

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[6] Some studies were made also of the stroke frequencies in characters of very long spelling. The results were remarkably close to those found for the complete vocabulary.

[7] August Dvorak, Patent No. 409,138 (United Kingdom).

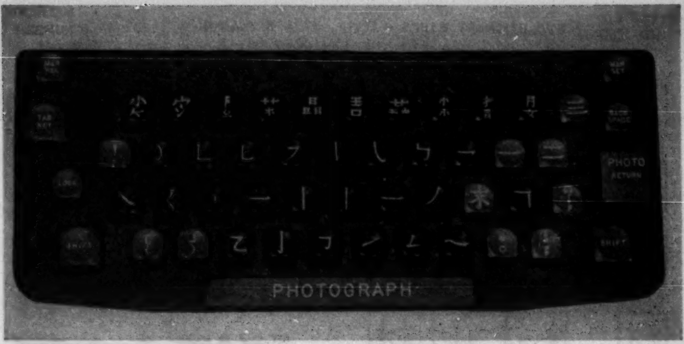

FIG. 10. The keyboard.

The keyboard arrangement shown in Fig. 10 was devised to take advantage of the known frequencies of Chinese strokes and supporting data on the frequencies of 2-stroke and 3-stroke sequences. It is rather striking that the horizontal stroke *B* and the vertical stroke *D* together account for more than half of all Chinese writing. If the diagonal stroke *G* and the dot *E* are added, these four strokes account for three quarters of the writing. On the keyboard the heavy contribution of the *B* and *D* strokes is reflected in the fact that keys for these strokes are made available to either hand.

There was some question whether the skill of a person who knew how to write Chinese would transfer readily to the process of setting up stroke sequences on a typewriter. Experiments were conducted with the cooperation of a number of Chinese students to examine this point. The number of subjects was too small to yield firm, quantitative answers, but almost without exception both the keyboard speed and the rate of committing errors showed marked improvement with very little practice.

One individual spent a total of 20 hours, divided into eight sessions, practicing keyboard operation. After the seventh and eighth sessions he was tested on unfamiliar prose samples, with the following results:

Session	Number of characters spelled	Number of errors	Number of correct characters	Total time, minutes	Correct characters per hour	Seconds per correct character
7	146	4	142	11	769	4.65
8	146	7	139	10	834	4.31

The above figures refer to characters spelled fully. Under actual machine operation, minimum spelling will prevail and substantial improvement in operating speed can be expected. There should also be a reduction in the number of errors, for it was observed during these tests that a majority of the errors occurred in the redundant part of the spelling.

Some studies were made of the effect of practice on the error rate. In Fig. 11 the curve of error rate as a function of practice time is a composite result to which a number of operators contributed. There seems good reason to expect that skill in writing Chinese characters will transfer readily to keyboard skill.

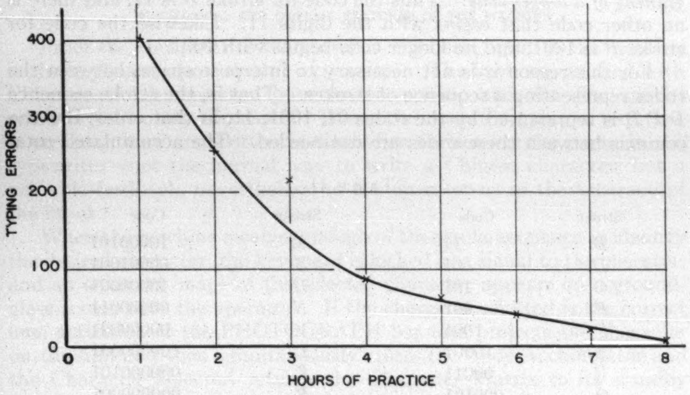

FIG. 11. Typing errors *versus* hours of typing practice.

The actual structure of the binary codes used to represent individual strokes is also influenced by the stroke frequency distribution. If codes of uniform length are used to represent all 21 strokes, these codes must all contain five binary digits, or bits. Since the longest characters require 20 strokes, a uniform-length code requires a maximum input description of 5 × 20 or 100 bits. Any reduction obtainable in the longest input code means a corresponding reduction in the sizes of the Code Accumulator and the Character Selector.

Such a reduction is readily obtained by the construction of a minimum-redundancy code.[8] In brief, the procedure is to assign short codes to the higher-frequency strokes and longer codes to strokes of lower frequency. Since Huffman's description of the method is quite complete, only the code finally derived is presented in Table II. The necessary stroke frequencies are given in Fig. 2.

In two respects the code presented in Table II is not quite a minimum-redundancy type. First, the "frequencies" of a few strokes were slightly, but arbitrarily, altered in order to reduce the code lengths of the longest characters. Second, in order to obtain certain desirable circuit advantages, all codes ending in "0" were augmented to end in "1." Despite these non-optimum procedures, the code length of the longest character is reduced to 68 bits from the 100 bits required using uniform-length stroke codes.

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[8] DAVID A. HUFFMAN, "A Method for the Construction of Minimum-Redundancy Codes," *Proc. I.R.E.*, Vol. 40, pp. 1098–1101 (1952).

An interesting and important characteristic of a minimum-redundancy code should be observed. *No code of any length forms the beginning of a longer code.* Thus the code for stroke *B* is 11, and there is no other code that *begins* with the digits 11. Likewise the code for stroke *P* is 1001, and no longer code begins with 1001.

For this reason it is not necessary to interpose spaces between the codes representing a sequence of strokes. That is, the stroke sequence *D P B* is represented by the codes 01, 1001, 11, in that order, but the commas between these codes are not needed. The accumulated total code 01100111 has no other possible interpretation than the stroke sequence *D P B*. Hence, when a sequence of key strokes produces binary code groups which are accumulated without spacing, there is no loss of identity. The uniqueness of all the stroke sequences is preserved in the sequences of binary digits which go finally to the Character Selector.

TABLE II.

Stroke	Code	Stroke	Code
B	11	*M*	10000101
D	01	*S*	00001001
G	101	*H*	10000001
E	001	*N*	00000011
P	1001	1	00000001
A	10001	*L*	100000001
V	00011	*Z*	000000101
Q	000101	*R*	000000001
J	000011	2	0000000001
Y	000001	*W*	0000001001
K	1000001	*T*	00000010001
X	1000011	3	000000100001
U	0000101		

Until more extensive operation of the machine has been completed, the statistics of Chinese writing cannot be given with complete confidence. If the entire vocabulary is studied without weighting for frequency of character occurrence, the median length of the full spellings is 10.2 strokes, and the median length of minimum spellings is 6.7 strokes. For a relatively small sample of actual prose text the median length of full spelling was 8.3 strokes and that of minimum spelling was 6.1 strokes. These figures suggest, by the sharp decrease in the length of full spelling, that a writer tends to select the simpler, and hence

V.2
195

shorter, characters, but there can be no firm conclusion on this point without considerably more data.

The effect of the use of entity keys has also been studied in small samples only. These studies indicate that the effect of using entity keys is to reduce *minimum* spelling about 23 per cent, that is, to about 4.7 strokes per character. This is a figure that compares remarkably with generally accepted figures for the average length of English words.

MECHANICAL AND OPTICAL FEATURES OF THE MACHINE

From the viewpoint of the operator, the basic input to the machine is the keyboard of an electric typewriter. The keys are marked with Chinese strokes, entities, punctuation points, and the few special symbols previously discussed. When the operator types a sequence of strokes, these are written in single-line fashion on the paper in the typewriter—not the normal way to write a Chinese character, but a valuable feedback, nevertheless, to the operator as to the accuracy of the input.[9]

When the machine receives enough of the stroke sequence to identify the desired character, the keyboard is locked as a signal to the operator, and an enlarged image of the selected character appears on a ground-glass screen near the operator. If the character selected is the correct one, actuation of the PHOTOGRAPH bar first projects the character on the film and then simultaneously resets the Code Accumulator and the Character Selector, returns the Character Matrix to its standby position, and prepares the optical system to project the next character in its correct position on the film.

If the selected character is not the correct one, actuation of the CANCEL key initiates the same resetting operations but does not change the projection position on the film.

In both cases, the operator is free to resume keyboard operation, either to select a new character or to correct an error. No modification is required when a character is found by the special keyboard action required to resolve ambiguity or to designate an "end of word," as previously discussed. Once a character is displayed on the screen, the operator either accepts or rejects it and goes on in the appropriate manner from there.

There are other important controls available to the operator. One of these rotates a lens turret to permit the selection of 9-, 12-, 18-, or 28-point composition size. Circuits which are modified by the turret position automatically change the spacing between characters and between lines, on the film, to correspond with the point size selected.

Another control permits the operator to select any of eight lengths of a line of composition, between 0.755 and 6.038 in., with intervals of 0.755 in. When the last character in a line is composed, the automatic control circuits return the prism carriage (to be discussed later) so that the next character is at the beginning of a new line, and also move the film the amount required to provide the correct distance between lines. This spacing between lines, known as "leading," also depends upon the point size of the composition.

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[9] It was not considered desirable in this model to introduce a procedure to "correct" an error by deleting an incorrect stroke and introducing the correct one. Instead, the operator actuates a CANCEL key and starts the stroke sequence from the beginning.

A unique feature of the control is the provision for changing at will from composition which reads in the older Chinese manner from top to bottom of columns arrayed from right to left on the page, to the more frequent modern manner of reading from left to right in rows arrayed from top to bottom on the page. Each character is displayed right-side-up on the operator's view screen, and normally the characters are projected to read from left to right in rows. However, by the introduction of a Dove prism in the optical path, the operator can rotate the characters 90° in a counter-clockwise direction (without rotating the display on the view screen). When the machine is now operated normally the effect is to convert the lines

T T T T T T T T T T
A A A A A A A A A A

to the lines

⊢ ⊢ ⊢ ⊢ ⊢ ⊢ ⊢ ⊢ ⊢ ⊢
∢ ∢ ∢ ∢ ∢ ∢ ∢ ∢ ∢ ∢.

If the page is now turned 90° in the clockwise direction it is apparent that the converted left-to-right reading lines have become right-to-left reading columns.

The Dove prism required for character rotation is located permanently in the optical path and its rotation is controlled by the operator by the use of a two-position switch.

A simplified diagram of the basic optical system is shown in Fig. 12.

V.2
195

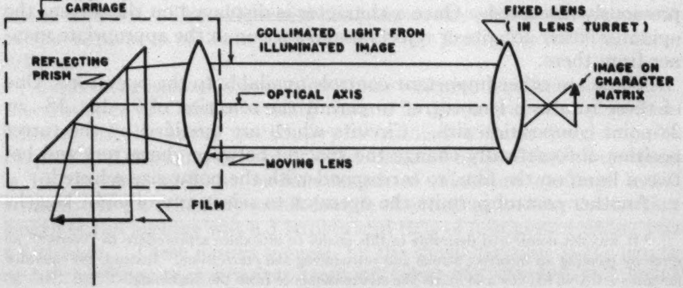
PRISM CARRIAGE
COLLIMATED LIGHT FROM ILLUMINATED IMAGE
FIXED LENS (IN LENS TURRET)
REFLECTING PRISM
IMAGE ON CHARACTER MATRIX
OPTICAL AXIS
MOVING LENS
FILM

FIG. 12. Basic optical system.

Each of the four (fixed) turret lens is adjusted so that any character brought to the optical axis of the system lies in the focal plane of the lens in use. When illuminated, the image of the character is at infinity; that is, the light leaving the fixed lens is collimated. This light is reflected through an angle of 90° by a prism, after passing through a lens mounted on a movable carriage. This second lens is maintained in a fixed position on the carriage, relative to the prism.

If a sheet of photographic film or paper is placed at the focal plane of the second lens, the original image is brought to focus. Moreover, the carriage may be moved parallel to the film and the projected image will remain in focus. Thus a relatively large supply of film can be stored in a magazine, with no need to move the film except to provide the leading between lines.

Two important elements of the optical system are not shown in Fig. 12. One of these is the Dove prism for rotating the image; this is located in the collimated beam close to the lens turret. The other is the shutter for exposing the selected character, together with an interlocked member carrying a prism for intercepting the image of the character and displaying it to the operator prior to photography.

The shutter is a simple plate containing an aperture, mounted on a pivoted arm, and passing between the matrix and the fixed lens. The intercepting prism is mounted on another pivoted arm and passes between the matrix and the shutter. When a character is located, the prism is first swung into position to intercept the light from the matrix for display to the operator (using an auxiliary optical system.) In this viewing position the prism mount prevents any light from reaching the fixed lens, so the shutter can be moved against a spring into the "ready" position without making an exposure. If the operator calls for PHOTOGRAPH, the elements of the system are interlocked so that first the prism returns to its standby position, after which the shutter, under spring drive, sweeps its aperture across the image to be more exposed.

If the operator gives the CANCEL signal, the prism member remains in its obstructing position while the shutter returns to the standby position. This action then permits the prism to return to the standby position with no exposure of the character.

A major mechanical element of the machine is the escapement which controls both the spacing of characters along a line and the leading of the film from one line to the next. Since these movements depend upon the size of the characters being composed, the mechanism must provide a variable escapement. This variation, however, need occur only in discrete steps. In the design, therefore, steps of 1, 2, and 4 units of spacing or leading can be released by associated half-turn clutches, actuated either singly or in any combination. These contributions are combined by planetary differential gears with the result that any escapement from 1 to 7 units is obtained, depending only on what combination of clutches is activated. Since the amount of escapement is established by the point size required, the clutch combination is set up by switches which are operated by appropriate cam lobes mounted on the lens turret.

An interesting feature of the escapement design is the method of avoiding high acceleration stresses in the prism carriage or in the film magazine.[10] The input to the escapement is a linear combination of a constant-speed rotation and an oscillatory rotation which is approximately sinusoidal in its variation, and which has a maximum rotational speed equal to that of the constant-speed component. When these two components are combined by a differential gear, the resulting input to the escapement has zero speed and zero acceleration at intervals determined by the frequency of the oscillatory component (five times per second.) Since the escapement clutches are phased mechanically so that they engage and release only at these zero-speed points, all shock to the load is avoided.

THE CHARACTER MATRIX AND ITS CONTROL

All vocabulary characters are contained in the matrix, an array of 50 columns and 48 rows. A portion of the matrix is shown in Fig. 13. Since each column–row intersection is a character "cell," the matrix has a capacity of 2400 characters. Some of the spaces are occupied by punctuation points, and many are occupied by the duplications of characters required to accommodate alternative spellings, as previously discussed. However, within the 2400 possible spaces there are 2333 different characters, all accessible by direct keyboard operation.

V.2
195

One character, located in the first column and the first row (see Fig. 13), is rather interesting. It was chosen because its somewhat complex structure makes it especially suitable for use in focusing the optical system. One of its meanings is "to adjust"—which was about as near the meaning "to focus" as the vocabulary contained.

But the position occupied by this character is of more immediate interest than either its structure, or its use in making optical adjustments. After each exposure of a character on film, the matrix is returned to a standby position to await the next horizontal and vertical coordinate signals which bring a newly selected character onto the optical axis. In the standby position the column 1 – row 1 area of the matrix is the one nearest to the optical axis. When the Character Selector signals that a character has been located, servomotors begin driving the matrix both horizontally and vertically, at approximately equal coordinate speeds, until solenoid-actuated stop pins are reached.

These stop pins are selected by the Character Selector circuits and

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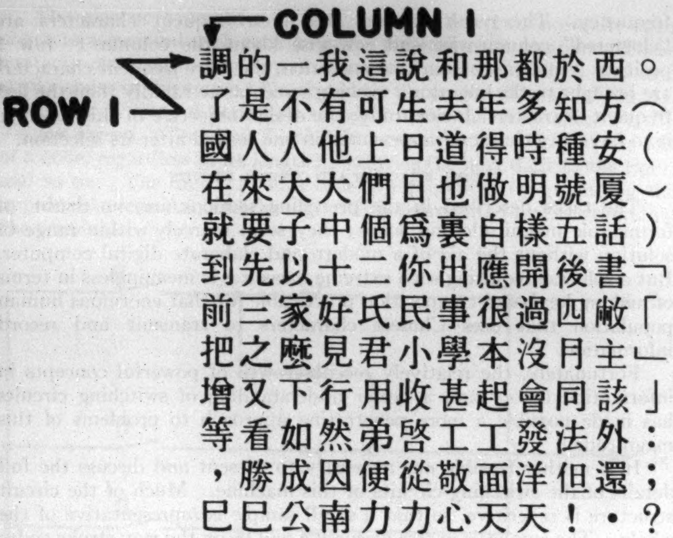
[10] It should be noted that, using a system of output clutches and controls, one escapement mechanism serves for both spacing and leading.



調的一我這說和那都於西。
了是不有可生去年多知方︵
國人人他上日道得時種安（
在來大大們日也做明號厦︶
就要子中個爲裏自樣五話）
到先以十二你出應開後書﹁
前三家好氏民事很過四敝「
把之麼見君小學本沒月主﹂
增又下行用收甚起會同該」
等看如然弟啓工工發法外：
，勝成因便從敬面洋但還；
巳巳公南力力心天天！•？

FIG. 13. A portion of the matrix.

the matrix is simply driven at full speed until they are encountered. If the horizontal pin is reached before the vertical pin, horizontal motion stops and the matrix frame slides along the horizontal stop pin until the vertical pin is reached, and vice versa.

This means that, assuming equal horizontal and vertical components of speed, the time required to move any character in the matrix from its standby position to the optical axis depends only upon its further distance, *either* horizontally or vertically, from that axis.

The column 1 – row 1 position is closest to the optical axis, and hence contains the character which requires the shortest possible time, after it has been selected, to appear on the operator's viewing screen. All characters in column 2 and/or row 2 likewise require approximately equal times to arrive at the optical axis. Generalizing, all characters in the *n*th row or the *n*th column are equidistant from the optical axis, under the assumption that the horizontal and vertical drive speeds are equal.

These considerations, together with the measured frequencies of occurrence of Chinese characters govern the makeup of the matrix. Each character of a given frequency is placed in a column – row location for which *neither* coordinate is larger than that of a character of smaller frequency. The result is that the more frequent characters are "clustered" column-wise and row-wise about the column 1 – row 1 position. In terms of machine operation, the more frequent characters are brought to the operator's viewing screen more rapidly than the less frequent characters. Incidentally, the design objective of this machine is to have any character appear within one second after its selection.

CODING, SELECTION AND CONTROL CIRCUITS

The tasks described in the preceding sections are, no doubt, of formidable magnitude and scope; they seem scarcely within range of solution without the aid of a modern and elaborate digital computer. But a solution requiring such extreme measures is meaningless in terms of making keyboard composition practicable for that enormous human population that uses Chinese characters to transmit and record information.

Fortunately, the relatively recent growth of powerful concepts in information theory and a better understanding of switching circuits has made possible a more penetrating approach to problems of this magnitude.[11]

It is neither feasible nor necessary to present and discuss the full details of the switching circuits of this machine. Much of the circuit structure is repetitive, so that a small sample is representative of the whole. The emphasis in this discussion will be on the way stroke codes are produced, transmitted, and accumulated to form character codes.

V.2
195

Table II shows that a single stroke requires the generation of a binary code containing from 2 to 12 digits. However, there are 20 entities available on the keyboard. Each of these is a sequence of strokes, so an entity code must be generated as a sequence of the codes representing the individual strokes. For example, the entity consisting of the stroke sequence *D P B* must contain, in the prescribed order, the code for *D* (01), *P* (1001), and *B* (11). Hence, when the *D P B* entity key is actuated, the code 01100111 must be transmitted to the Code Accumulator.

It is a noteworthy characteristic of the minimum-redundancy code used that, although the 20 entities available on the keyboard contain at least three and at the most seven strokes, the maximum length of an entity code is only 17 digits, compared to 12 digits for the maximum length of a single stroke code. The keyboard unit of the machine must therefore be capable of transmitting, in response to a single key operation, binary codes of from 2 to 17 digits in length, and the Code Accumulator must be capable of receiving these codes, and of combining them in sequence to form character codes of up to 68 digits in length.

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[11] Huffman's work on the construction of minimum-redundancy codes is used importantly in the design of this machine. For the general aspects of switching circuits, see S. H. CALDWELL, "Switching Circuits and Logical Design," New York, John Wiley & Sons, Inc., 1958.

The electric typewriter in this machine has two normally-open contacts associated with each key, one for each shift position. These contacts close when the key is depressed and are used to generate stroke codes in the manner illustrated by the partial diagram of Fig. 14. There are 17 output terminals of which only the first three, T_1, T_2, T_3, are shown. Terminal T_1 *always* carries the first digit on the left of a code, regardless of its length; T_2 carries the next digit to the right, and so on. The digit "1" in a code is represented by grounding the appropriate terminal, and the digit "0" is represented by not grounding the terminal.

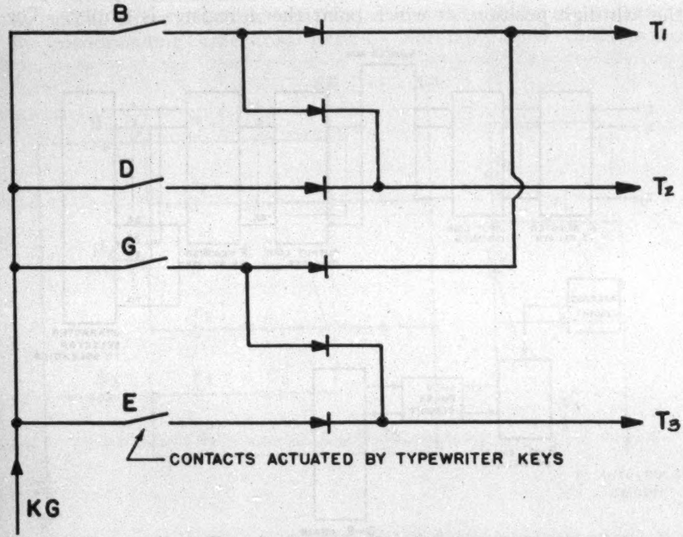

FIG. 14. Generation of stroke codes.

In Fig. 14 the circuits for generating the stroke codes *B* (11), *D* (01), *G* (101), and *E* (001), are shown. The actuation of any key causes the input *KG* to be grounded. Then through the individual contact closed by the key this ground is distributed to all the terminals that correspond to the 1's in the code. Rectifiers must be used in each distribution line to prevent the generation of false codes. For example, terminal T_2 is grounded for either the 11 code of stroke *B*, or the 01 code of stroke *D*. However, without the rectifiers, if the *D* contact is closed, ground would appear not only on T_2, but it would "back up" through the connection from *B* to T_2 and thence appear, incorrectly, on T_1.

Stroke codes thus generated appear on the terminals T_1, $T_2 \cdots T_{17}$ of the schematic diagram of the Code Accumulator shown in Fig. 15. These terminals are the inputs to the A register where the stroke code is temporarily stored. Each stroke code is then read out of the A register as a time sequence and read into the F register to form the ensemble which becomes the character code. This operation is controlled by the synchronous stepping action of the $B - C$ and $D - E$ chains which ensures that the input and output link circuits connect each position of the A register to the correct destination position in the F register.

When the first stroke of a character appears, the $B - C$ and $D - E$ chains both start in the first digit position and step synchronously to the nth digit position, at which point the A register is empty. The $B - C$ chain then returns to the first digit position and the $D - E$ chain advances to the $(n + 1)$ digit position. Consequently, when the next stroke appears in the A register, its first digit is transmitted to the $(n + 1)$ position in the F register, after which the remaining digits are transmitted to successive positions in the F register. After each stroke code is read out in full, the $B - C$ chain returns to the first position and the $D - E$ chain advances to the next digit position.

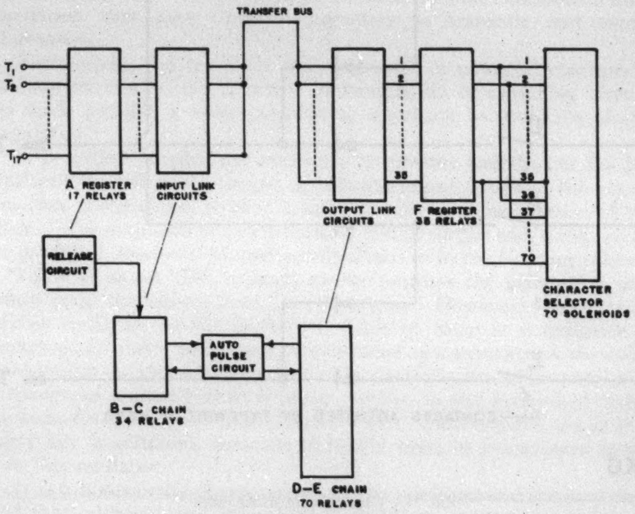
TRANSFER BUS
T1
T2
T17
A REGISTER 17 RELAYS
INPUT LINK CIRCUITS
1
2
35
OUTPUT LINK CIRCUITS
F REGISTER 35 RELAYS
1
2
35
36
37
70
CHARACTER SELECTOR 70 SOLENOIDS
RELEASE CIRCUIT
AUTO PULSE CIRCUIT
B-C CHAIN 34 RELAYS
D-E CHAIN 70 RELAYS

FIG. 15. Code Accumulator.

The F register transfers its information directly to the Character Selector. Actually, the F register is needed only to receive and store

V.2
195

code digits at high speed so that they continue to be available to the Character Selector which operates at relatively slow speed.

The Character Selector can receive codes up to 70 digits in length. Since only about 15 per cent of the characters require more than 35 digits, a special changeover circuit is used so that after the *F* register receives the first 35 digits, and has transmitted them to the Character Selector in positions 1 to 35, the *F* register releases all previously stored digits and becomes reconnected to serve positions 36 to 70 in the Character Selector. The same changeover circuit also resets the $D-E$ chain from position 35 back to position 1.

In the circuit diagrams now to be discussed, relay coils are designated by capital letters and subscripts; contacts on those relays are designated by corresponding lower-case letters. Normally open contacts are marked by unprimed designators and normally closed contacts have primed designators.

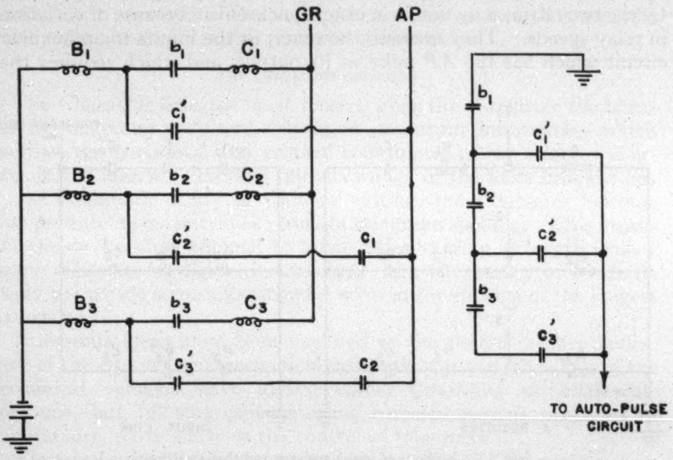

FIG. 16. Typical section of a stepping chain and associated pulse generator.

At the left of Fig. 16 is a diagram of the first three positions of the $B-C$ stepping chain. In normal operation the input *GR* is solidly grounded and the input *AP* receives a pulsed ground. All relays are released when the *GR* ground is removed.

Assume that all relays are released and that there is a ground on *GR* only. No relays can operate because the *b* contacts between each $B-C$ pair are open. If ground is now applied to the *AP* input it operates B_1 through the c_1' contact. Contact b_1 now closes but relay

C_1 does not operate because it is grounded at both coil terminals. If the *AP* ground is now removed C_1 operates in series with B_1, and the c_1' contact opens in the $B_1 - C_1$ circuit. These two relays will remain operated until the *GR* ground is removed. The operation of relay C_1, however, closes the c_1 contact in the next stage and enables the *AP* ground to reach relay B_2.

When a ground is alternately applied to and removed from the *AP* terminal of this chain the relays operate and hold in the sequence $B_1 - C_1 - B_2 - C_2 - B_3 - C_3$, etc. At the right of Fig. 16 there is a section of a contact network which produces a ground to indicate that the chain has reached the point where a relay B_n has operated and relay C_n has not operated. The $D - E$ chain is of exactly the same structure as the $B - C$ chain and it also contains a circuit to show when D_n has operated and E_n has not operated. These two pulsed grounds generated by the two chains may not be in exact synchronism because of variations in relay speeds. They are used, however, as the inputs to an auxiliary circuit which has the *AP* pulse as its output, and which requires that both chains reach corresponding conditions before allowing the *AP* signal to change. Thus the two chains must operate synchronously and they generate the signals which permit this operation at maximum speed.

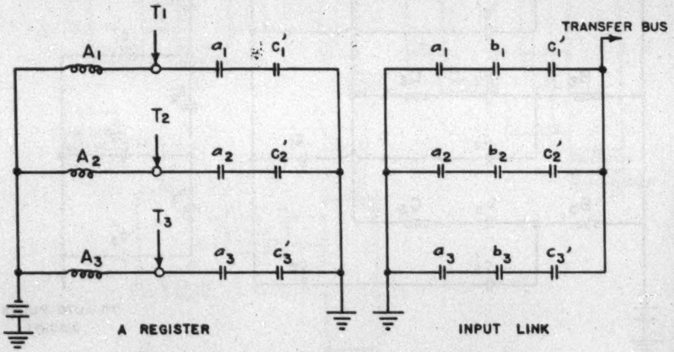

FIG. 17. Sections of the A register and the input link.

At the left of Fig. 17 is a section of the *A* register. A ground appearing on a terminal T_n causes A_n to operate and to remain operated through the a_n and c_n' contact path.

The operation of any relay in the *A* register causes the $B - C$ and $D - E$ chains to begin stepping. As the $B - C$ chain steps, the operation of its successive *C* relays releases the *A* relays. Since the last code

V.2
195

digit is always a "1," the release of the last A relay signals the fact that all digits have been read out. This leads to the resetting of the $B - C$ chain as previously described.

In the process of scanning and clearing the A register the circuit at the right of Fig. 17 examines the contents of the register for "1" digits and for each of these it transmits a ground, at exactly the right time, to the F relay which has been connected to the transfer bus by a similar circuit, using contacts from the $D - E$ chain. It will be noted that if any A relay is operated ground will propagate through its closed a contact only at the moment when the $B - C$ chain has the corresponding B relay operated and the C relay not operated. At the F register, each F relay coil connects to the transfer bus through d and e' contacts in series. Operation of an F relay occurs then if the A relay is operated and if the two stepping chains are in the condition B and D operated, C and E not operated. The auto-pulse system assures that the two chains must always be in this phase simultaneously.

THE CHARACTER SELECTOR

The Character Selector must receive from the F register the accumulated character code and deliver as its output information which describes the horizontal and vertical coordinates of the selected character in the matrix. To take full advantage of the facts brought out by the systematic study of Chinese writing, the Character Selector must produce its output on the basis of minimum spelling. This means that the device must respond to input codes varying in length from 7 binary digits to 68 digits (it was built with a capacity of 70 digits simply to provide some allowance for error in the spelling of the longest characters).

Numerous ideas have been explored in the design of this device. Most of these have been mechanical rather than electrical. Two of the mechanical versions have looked rather promising in small-scale mock-ups, but full-size considerations revealed serious problems of manufacture, particularly in the control of tolerances.

Electrical solutions are not conspicuously better. The construction tolerances can be broadened but other problems arise. Nevertheless, it was finally decided to proceed with a relatively simple electrical solution for the present model, realizing that it was by no means an ideal solution.

Essentially, the procedure is to set up 2400 contact networks, only one of which is closed upon the introduction of a valid stroke sequence (or the depression of a punctuation key). In order to do this it is necessary to arrange, for each character, a series connection of contacts. Whenever a digit in the character code is "0" a normally-closed contact must be used. But if the code digit is "1" a normally-open contact must be closed by a mechanical movement.

These conditions can be satisfied entirely by relays, but even using the multi-contact types now available an extremely bulky system is involved. The method finally adopted uses a special design for the contact control of the first 40 positions in the character code. Beyond this point, commercial relays of progressively decreasing contact capacities are used.

A type of multiple-fingered contact strip developed for use in joining segments of radar wave guides was adapted to form the contacts for the first 40 positions of the character code. This contact strip was produced on punch presses in continuous strip form, as illustrated in Fig. 18. Originally produced with all its contact fingers uniformly spaced, the manufacturer made special dies to produce the strips with the fingers spaced in groups of three. These strips were than held in special fixtures and cast in epoxy resin plates in parallel rows so that the contact fingers protruded from the epoxy, with the contact surfaces of each pair of rows facing inwards. After casting, the longitudinal strip, to which the contact fingers are attached, is removed.

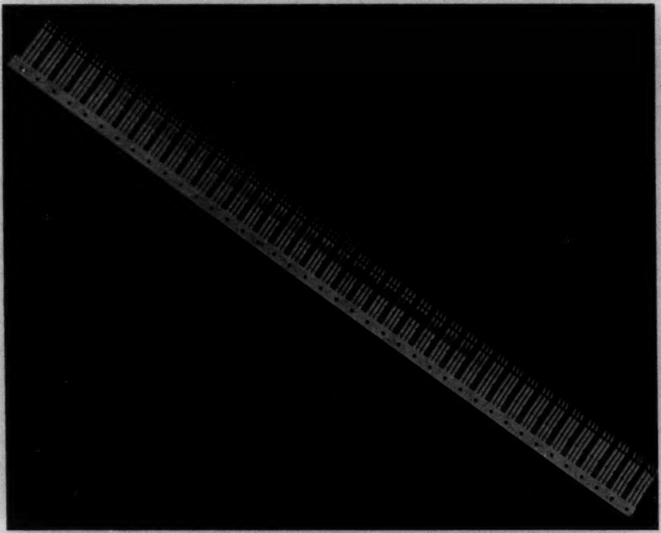

FIG. 18.

Between each pair of rows a strip of insulating material is introduced. This strip has segments of conducting material on its surfaces adjacent to the contact fingers. The conducting segments are arranged so that

V.2
195

	A	B	C
X	1	2	3
Y	4	5	6
Z	7	8	9

FIG. 19. A simplified matrix.

if the strip is not moved from its normal, or undisplaced, position contact is established between the center of each group of three fingers to one of the outside fingers. This is considered the position corresponding to a "0" in a character code. If the digit "1" is received, the strip is moved so that its conducting segment establishes contact between the center finger and the other outside finger.

By this process thousands of transfer contacts are built within relatively small dimensions. The fact that only normally open or normally closed contacts are needed is immaterial; it is cheaper to build all the contacts as transfer contacts and use only the normally open or normally closed part of each.

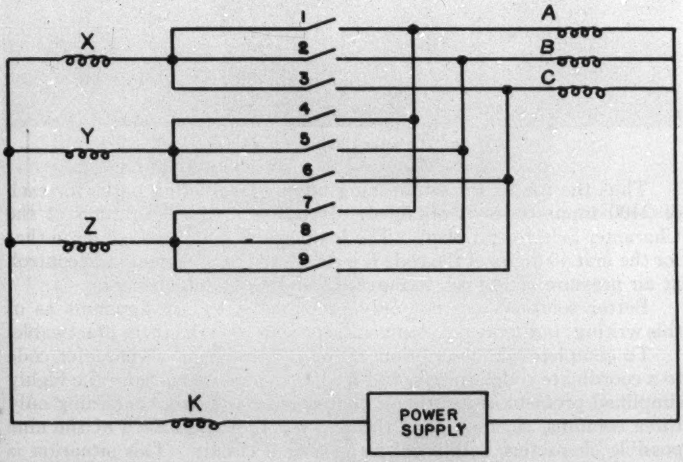

FIG. 20. Basic circuit for matrix control.

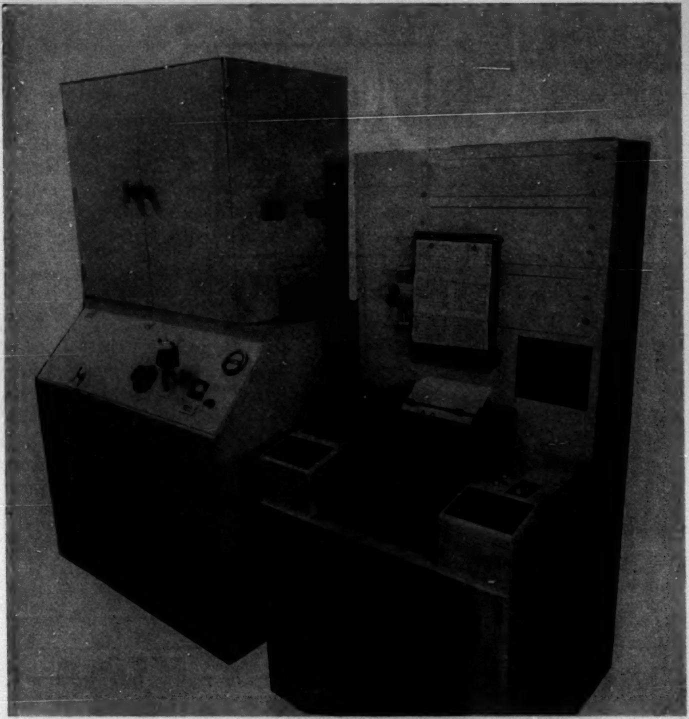

FIG. 21. Over-all view of machine.

Thus the means for establishing unique conducting paths for each of 2400 input codes is obtained. It is not an ideal solution of the Character Selector problem. The load on the switches is so large that for the first 40 digits of the code it is necessary to use pneumatic control, at air pressure of 140 psi. to move the sliding switch elements.

Better solutions are not only probable—they are apparent as of this writing; but more development is needed to make them practicable.

To complete the description of the conversion of a character code to a coordinate code, we refer to Fig. 19. There we consider the highly simplified problem of locating a character in a matrix containing only three columns, A, B, C, and three rows, X, Y, Z. Each of the nine possible characters is selected by closing a circuit. This situation is represented in Fig. 20 by the switches numbered from 1 to 9. On the

V.26
195

left the various possible paths are grouped to pass through coils *X*, or *Y*, or *Z*, which are solenoids actuating the vertical stop pins of the matrix control system. At the right of Fig. 20, the possible paths are grouped to energize solenoid *A*, or *B*, or *C*, which actuate the horizontal stop pins of the matrix control. The extension of this idea to a 50 × 48 matrix is complex, but obvious.

In Fig. 20, the relay *K*, in series with the power supply, is actuated if *any* character is located. This relay carries a number of contacts which initiate many of the functions of the machine. It is not respon-

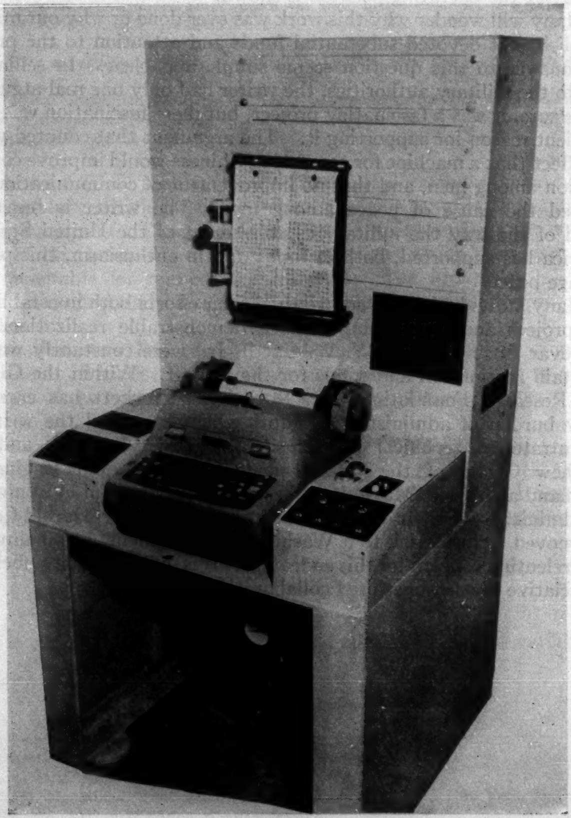

FIG. 22. View showing operator's position.

sible, however, for the raised eyebrows of the operator who finds the machine displaying the desired character before he completes its spelling.

CONCLUDING REMARKS

This machine is by no means the final answer to the problem, but it does represent an important forward step. Its greatest importance is that it demonstrates that the objective of composing Chinese from a keyboard is possible.

The machine as a whole is shown (during final assembly) in Fig. 21. In Fig. 22 the operating position is shown.

Many will wonder why this work was ever done or why our military establishment devoted substantial funds and attention to the project. The answer to this question seems simple and clear. In selling the idea to the military authorities, the writer had only one real argument. To be sure, it was a fascinating project, but mere fascination was not a sufficient reason for supporting it. The argument that counted was to the effect that a machine for composing Chinese would improve communication among men, and that no improvement of communication ever harmed the cause of peace among men. The writer is burstingly proud of the way the military establishment of the United States of America has supported, both in funds and in enthusiasm, this project to wage peace.

Many individuals have contributed their efforts both in establishing this project and in carrying it to a demonstrable realization. Dr. Vannevar Bush and Mr. W. W. Garth, Jr., were constantly working to obtain recognition and funds for the project. Within the Graphic Arts Research Foundation, Mr. Robert G. Crockett has carried a heavy burden of administrative effort which has freed the writer to concentrate on technical problems. Mr. T. S. Bonczyk and Mr. Matthew Griffin of the Quartermaster Research and Engineering Command at Natick, Mass., have been especially helpful in ironing out the administrative snags of a government project. Mr. Harold Cotner, who moved from Natick to a Washington assignment, has maintained an unrelenting concern for this endeavor. It is difficult to be sufficiently appreciative of such unstinted collaboration.

V.26
1959

A REDUCED SOLUTION FOR THE SIMPLE PENDULUM: NEW APPROACH TO ELLIPTIC FUNCTIONS

BY

LOUIS GOLD [1]

ABSTRACT

A novel attack of the simple pendulum leads to the discovery of a powerful manner for characterizing elliptic functions. In particular, elliptic functions of the first kind are expressible in terms of a fractional power series $\sum_{n=0}^{\infty} a_{n+1}\phi^{n+1/2}$ where ϕ is an angular displacement variable and the a_i coefficients derive from an appropriate inverse differential equation for the pendulum motion. The correspondence between such a power series and the conventional elliptic integrals is pointed out.

A novel method for solving the classic simple pendulum problem is presented here which introduces an alternative manner for expressing elliptic functions. Thus, a concise power series replaces the conventional elliptic integral (or its series expansion) which turns out to be more amenable for numerical evaluation. The formalism is closely allied to that already developed in connection with inverse Bessel functions.[2]

This discovery has general significance in the domain of elliptic functions of all kinds; but, treatment here will be restricted to elliptic functions of the first kind which associate with the pendulum.

DEVELOPMENT OF THE INVERSE SERIES ANALYSIS

Various ramifications of the conventional theory of the simple pendulum are amply described in the literature.[3] Here attention is focussed on the oscillatory solution only, where the prevailing boundary conditions are

$$t = 0, \quad d\theta/dt = 0, \quad \theta = \theta_0 < \frac{\pi}{2}.$$

It is convenient at the outset to deal with the modified variables

$$\tau = \sqrt{\frac{g}{l}}\, t, \quad \phi = \theta_0 - \theta \tag{1}$$

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[1] Edgerton, Germeshausen and Grier, Inc., Boston, Mass.

[2] L. Gold, *J. Math. and Phys.*, Vol. 36, p. 167 (1957).

[3] W. D. MacMillan, "Statics and the Dynamics of a Particle," New York, McGraw-Hill Book Co., Inc., 1927, first edition, p. 310 *et seq.*

whereby the standard pendulum equation assumes the form

$$\frac{d^2\phi}{d\tau^2} = -\sin(\phi - \theta_0). \tag{2}$$

Now an inverse solution $\tau = f(\phi)$ may be found by noting that

$$\frac{d^2\phi}{d\tau^2} = \frac{-f''(\phi)}{[f'(\phi)]^3} \tag{3}$$

whence the inverse differential equation for (2) becomes

$$f''(\phi) + \sin(\theta_0 - \phi)[f'(\phi)]^3 = 0. \tag{4}$$

Integration of (4) leads to the first order equation

$$[f'(\phi)]^2[\cos(\theta_0 - \phi) - \cos\theta_0] - \tfrac{1}{2} = 0 \tag{5}$$

for which an indicial series solution is next posed:

$$\tau = f(\phi) = a_1\phi^{\nu} + a_2\phi^{\nu+p} + \cdots. \tag{6}$$

The value $\nu = \frac{1}{2}$ follows from the boundary conditions, while $p = 1$ is prescribed by direct substitution of (6) into (5).

Thus the inverse solution has the character

$$\tau = f(\phi) = a_1\phi^{1/2} + a_2\phi^{3/2} + a_3\phi^{5/2} + \cdots \tag{7}$$

where the a_i

$$\begin{aligned} a_1 &= \left(\frac{2}{\sin\theta_0}\right)^{1/2}, \quad a_2 = \frac{1}{24}\left(\frac{2}{\sin\theta_0}\right)^{3/2}\cos\theta_0, \\ a_3 &= \frac{1}{60}\left(\frac{2}{\sin\theta_0}\right)^{1/2}\left[\frac{9}{32}\left(\frac{2}{\sin\theta_0}\right)^2\cos^2\theta_0 + 1\right], \text{ etc.} \end{aligned} \tag{8}$$

are evaluated in the manner of Appendix I.

DELINEATION OF THE PERIOD FROM THE INVERSE POWER SERIES

For the initial conditions stated, the period T follows from the circumstance $t = \frac{1}{4}T$ for $\theta = 0$, whence there obtains according to (7) and (8)

$$T = 4\sqrt{\frac{l}{g}}\,S(\theta_0) \tag{9a}$$

wherein the series $S(\theta_0)$ is given by

$$S(\theta_0) = \left(\frac{2\theta_0}{\sin\theta_0}\right)^{1/2}\left\{1 + \frac{1}{24}\cos\theta_0\left(\frac{2\theta_0}{\sin\theta_0}\right) + \frac{1}{60}\left[\frac{9}{32}\cos^2\theta_0\left(\frac{2}{\sin\theta_0}\right)^2 + \theta_0^2\right] + \cdots\right\}. \tag{9b}$$

Note, significantly, the absence of the characteristic quantity π in this alternative relation for the period; the conventional expression is stated below for comparison:

$$T = 2\pi\sqrt{\frac{l}{g}}\left(1 + \frac{1}{4}k^2 + \frac{9}{64}k^4 + \cdots\right),\quad k^2 = \sin^2\frac{\theta_0}{2}. \tag{10}$$

If the small amplitude limit $\theta_0 \to 0$ is considered, the equivalence of Eqs. 9 and 10 may be readily demonstrated.

Hence it follows that

$$\underset{\lim\theta_0\to 0}{T} = 4\sqrt{2}\sqrt{\frac{l}{g}}S(0) = 2\pi\sqrt{\frac{l}{g}} \tag{11}$$

in which the numerical series $S(0)$ is

$$S(0) = 1 + \frac{2}{24} + \frac{3}{640}\cdot 2^2 + \cdots \tag{12}$$

with the higher members more simply determined by dealing directly with the small amplitude solution as described in Appendix II. It turns out then that the general form of (12) can be expressed in this manner:

$$S(0) = 1 + \sum_{n=1}^{\infty}\frac{2n-1}{2n+1}\cdot\frac{1}{2^{(3n-1)}}. \tag{13}$$

The Cauchy ratio test reveals that the series $S(0)$ is rapidly convergent with

$$r = \frac{V_{n+1}}{V_n} = \frac{1}{2^3}\cdot\frac{(2n+1)^2}{(2n+3)(2n-1)} \tag{14}$$

whereby the bounds on r evidently are

$$\frac{9}{5}\cdot\frac{1}{2^3} \geq r \geq \frac{1}{2^3}.$$

Furthermore, the finding (11) offers a convenient means for calculating the value of π (in what may prove to be a better operational manner) via

$$\pi = 2\sqrt{2}S(0) \tag{15}$$

since as already pointed out the series (13) is rapidly convergent; not to be overlooked is the inherent improvement of (13) over most inverse trigonometric series expansions.

COMPARISON BETWEEN FRACTIONAL POWER SERIES AND ELLIPTIC INTEGRALS

Before entering into this matter, it is important to observe the distinction between the θ value at $t = 0$ for the present analysis and the conventional one, thereby avoiding confusion. With this in mind, it is helpful to denote the angular variables for the two cases by the subscripts s and Σ which associate, respectively, with the elliptic integral form and the present one. Thus, the needed quantities are

$$\sin\frac{\theta_s}{2} = \sin\frac{\theta_0}{2}\sin\phi_s,\quad t = 0,\quad \theta_s = \frac{\pi}{2} \text{ (elliptic integral)}$$

$$\phi_\Sigma = \theta_0 - \theta_\Sigma,\quad t = 0,\quad \theta_\Sigma = 0 \text{ (fractional power series)}$$

with the simple result

$$\theta_\Sigma = \frac{\pi}{2} - \theta_s. \tag{16}$$

Now the fractional power series (7) may be equated with the incomplete integral of the first kind:

$$f(\phi_\Sigma) = f(k, \phi_s)$$

or explicitly

$$\sum_{n=0}^{\infty} a_{n+1}\phi_\Sigma^{n+1/2} = \int_0^{\phi_s}\frac{d\phi_s}{\sqrt{1 - k^2\sin^2\phi_s}},\quad k^2 = \sin^2\frac{\theta_0}{2}. \tag{17}$$

Then, cognizant of the result (16), the complete integral correspondence has

$$f(\theta_0) = f\left(k, \frac{\pi}{2}\right) \equiv K$$

or

$$K \equiv \int_0^{\pi/2}\frac{d\phi_s}{\sqrt{1 - k^2\sin^2\phi_s}} = \sum_{n=0}^{\infty} a_{n+1}\theta_0^{n+1/2}. \tag{18}$$

At this juncture, the superiority of the new means for expressing the elliptic functions clearly emerges. It will be recalled that the complete elliptic function as utilized in (10) derives from the power expansion of the elliptic integral in (18), followed by the application of Wallis' formula. The fractional power series is particularly valuable for the incomplete elliptic functions since the sum in (17) is intrinsically much easier to deal with than the equivalent integral.

V.2
195

CONCLUSION

The inverse solution is invoked for the pendulum problem because of its convenience for determining the period of oscillation. The fractional power series form permits straightforward deduction of the customary non-inverted solution. A reversion analysis as carried out in Appendix III reveals that the power series for $\phi(\tau)$ given by

$$\phi(\tau) = \tau(b_1\tau + b_2\tau^2 + b_3\tau^3 + \cdots) \tag{19}$$

satisfies Eq. 2 for the required initial conditions with the b_i related to the a_i of (8) as follows:

$$b_1 = \frac{1}{a_1^2}, \quad b_3 = -2\frac{a_2}{a_1^5}, \quad b_5 = \frac{1}{a_1^8}(7a_2^2 - 2a_1a_3),$$
$$b_2 = b_4 = b_{2n} = 0, \quad n = 1, 2, 3, \cdots. \tag{20}$$

As demanded by the physical nature of the pendulum phenomenon, the parity of τ and $-\tau$ necessitates that the even coefficients b_{2n} vanish.

Hence the elaborated solution for ϕ becomes

$$\phi = \left(\frac{1}{2}\sin\theta_0\right)\tau^2 - \left(\frac{1}{48}\sin 2\theta_0\right)\tau^4 + \frac{1}{240}\sin\theta_0\left(\frac{4}{3}\cos^2\theta_0 - 1\right)\tau^6 \tag{21}$$

which for the limiting case of small amplitudes, where $\theta_0 \to 0$, reduces to

$$\frac{\theta}{\theta_0} = 1 - \frac{1}{2}\tau^2 + \frac{1}{24}\tau^4 - \frac{1}{720}\tau^6 + \cdots. \tag{22}$$

The series (21) evidently corresponds to cos τ in accordance with the anticipated simple harmonic motion having the periodicity defined by $\tau = 2\pi$ or $T = 2\pi\sqrt{\frac{l}{g}}$.

APPENDIX I

The a_i coefficients derive as follows:

$$f'(\phi) = \frac{1}{2}a_1\phi^{-1/2} + \frac{3}{2}a_2\phi^{1/2} + \frac{5}{2}a_3\phi^{3/2} + \cdots$$

$$[f'(\phi)]^2 = \frac{1}{4}a_1^2\phi^{-1} + \frac{3}{2}a_1a_2 + \left(\frac{9}{4}a_2^2 + \frac{5}{2}a_1a_3\right)\phi$$
$$+ \left(\frac{7}{2}a_1a_4 + \frac{15}{2}a_2a_3\right)\phi^2 + \left(\frac{25}{4}a_3^2 + \frac{9}{2}a_1a_5 + \frac{21}{2}a_2a_4\right)\phi^3 + \cdots$$

267
59

$$[f'(\phi)]^3 \cos\phi = \frac{1}{4}a_1^2\phi^{-1} + \frac{3}{2}a_1a_2 + \left(\frac{9}{4}a_2^2 + \frac{5}{2}a_1a_3 - \frac{1}{8}a_1^2\right)\phi$$

$$+ \left(\frac{7}{2}a_1a_4 + \frac{15}{2}a_2a_3 - \frac{3}{4}a_1a_2\right)\phi^2$$

$$+ \left[\frac{25}{4}a_3^2 + \frac{9}{2}a_1a_5 + \frac{21}{2}a_2a_4 - \frac{1}{2}\left(\frac{9}{4}a_2^2 + \frac{5}{2}a_1a_3\right) + \frac{1}{4}\cdot\frac{1}{4!}a_1^2\right]\phi^3 + \cdots$$

$$[f'(\phi)^3] \sin\phi = \frac{1}{4}a_1^2 + \frac{3}{2}a_1a_2\phi + \left(\frac{9}{4}a_2^2 + \frac{5}{2}a_1a_3 - \frac{1}{4}\cdot\frac{1}{3!}a_1^2\right)\phi^2$$

$$+ \left(\frac{7}{2}a_1a_4 + \frac{15}{2}a_2a_3 - \frac{3}{2}\cdot\frac{1}{3!}a_1a_2\right)\phi^3$$

$$+ \left(\frac{25}{4}a_3^2 + \frac{9}{2}a_1a_5 + \frac{21}{2}a_2a_4 + \frac{1}{4}\cdot\frac{1}{5!}a_1^2 - \frac{9}{4}\cdot\frac{1}{3!}a_2^2 - \frac{1}{3!}\right.$$

$$\left. + \left[\frac{9}{2}a_2^2 + \frac{5}{2}a_1a_3\right]\right)\phi^4 + \cdots.$$

Equating coefficients leads to

$$\phi^{-1}:\quad \frac{1}{4}a_1^2\cos\theta_0 - \frac{1}{4}a_1^2\cos\theta_0 = 0$$

$$\text{Const}:\quad \frac{3}{2}a_1a_2\cos\theta_0 + \frac{1}{4}a_1^2\sin\theta_0 - \frac{3}{2}a_1a_2\cos\theta_0 - \frac{1}{2} = 0$$

$$\phi:\quad \left(\frac{9}{4}a_2^2 + \frac{5}{2}a_1a_3 - \frac{1}{8}a_1^2\right)\cos\theta_0 + \frac{3}{2}a_1a_2\sin\theta_0 - \left(\frac{9}{4}a_2^2 + \frac{5}{2}a_1a_3\right)\cos\theta_0 = 0$$

$$\phi^2:\quad \left(\frac{7}{2}a_1a_4 + \frac{15}{2}a_2a_3 - \frac{3}{4}a_1a_2\right)\cos\theta_0$$

$$+ \left(\frac{9}{4}a_2^2 + \frac{5}{2}a_1a_3 - \frac{1}{4}\cdot\frac{1}{3!}a_1^2\right)\sin\theta_0 - \left(\frac{7}{2}a_1a_4 + \frac{15}{2}a_2a_3\right)\cos\theta_0 = 0.$$

Thus the values given in (8) are arrived at.

APPENDIX II

Characterization of the series $S(0)$ resulting from Eq. 9 in the limit of $\theta_0 \to 0$ may be performed by applying the expansion procedure directly to $d^2\theta/d\tau^2 = -\theta$. Thus Eq. 7 now is the solution for

$$f''(\phi) - (\phi - \theta_0)[f'(\phi)]^3 = 0$$

whereby as in Appendix I the coefficients evaluate from

$$\phi^{-3/2}:\quad -\frac{1}{4}a_1 + \frac{1}{8}\theta_0a_1^3 = 0$$

$$\phi^{-1/2}:\quad \frac{3}{4}a_2 + \frac{9}{8}a_1^2a_2\theta_0 - \frac{1}{8}a_1^3 = 0$$

$$\phi^{1/2}:\quad \frac{15}{4}a_3 + \frac{3}{8}(9a_1a_2^2 + 5a_1^2a_3)\theta_0 - \frac{9}{8}a_1^2a_2 = 0$$

$$\phi^{3/2}:\quad \frac{35}{4}a_4 + \left(\frac{7}{8}a_1^2a_4 + \frac{15}{2}a_1a_2a_3 + \frac{27}{8}a_2^3\right)\theta_0 - \frac{3}{8}(9a_1a_2^2 + 5a_1^2a_3) = 0,$$

etc. In place of (8), then, there obtain

$$a_1 = \left(\frac{2}{\theta_0}\right)^{1/2}, \qquad a_2 = \frac{1}{24}\left(\frac{2}{\theta_0}\right)^{3/2}, \qquad a_3 = \frac{3}{5}\cdot\frac{1}{128}\left(\frac{2}{\theta_0}\right)^{5/2}$$

$$a_4 = \frac{5}{7}\cdot\frac{1}{2^{11}}\left(\frac{2}{\theta_0}\right)^{7/2}, \cdots a_\nu = \frac{2(\nu-1)-1}{2(\nu-1)+1}\cdot\frac{1}{2^{4(\nu-2)+3}}\left(\frac{2}{\theta_0}\right)^{(\nu-1/2)} \qquad \nu > 1.$$

APPENDIX III

To invert the series (7), it is helpful to first convert to the result

$$\tau^2 = a_1^2\phi + 2a_1a_2\phi^2 + (a_2^2 + 2a_1a_3)\phi^3 + 2(a_1a_4 + a_2a_3)\phi^4 + \cdots.$$

Then from the expansion (18) there calculate

$$\begin{aligned}
\phi^2 &= \tau^2[b_1^2\tau^2 + 2b_1b_2\tau^3 + (b_2^2 + 2b_1b_3)\tau^4 + 2(b_1b_4 + b_2b_3)\tau^5 + \cdots]\\
\phi^3 &= \tau^3[b_1^3\tau^3 + 3b_1^2b_2\tau^4 + 3(b_1b_2^2 + b_1^2b_3)\tau^5 + \cdots]\\
\phi^4 &= \tau^4[b_1^4\tau^4 + 4b_1^3b_2\tau^5 + (6b_1^2b_2^2 + 4b_1^3b_3)\tau^6 + \cdots].
\end{aligned}$$

Hence equating coefficients produces

$$\begin{aligned}
\tau^2&:\quad a_1^2b_1 = 1\\
\tau^3&:\quad a_1^2b_2 = 0\\
\tau^4&:\quad a_1^2b_3 + 2a_1a_2b_1^2 = 0\\
\tau^5&:\quad a_1^2b_4 + 4a_1a_2b_1b_2 = 0\\
\tau^6&:\quad a_1^2b_5 + 2a_1a_2(b_2^2 + 2b_1b_3) + (a_2^2 + 2a_1a_3)b_1^3 = 0\\
\tau^7&:\quad a_1^2b_6 + 4a_1a_2(b_1b_4 + b_2b_3) + 3b_1^2b_2(a_2^2 + 2a_1a_3) = 0,
\end{aligned}$$

from which the results in (20) follow. Explicitly the terms in (21) contain

$$b_1 = \frac{1}{2}\sin\theta_0, \qquad b_3 = -\frac{1}{48}\sin 2\theta_0$$

$$b_5 = \frac{\sin\theta_0}{240}\left(\frac{4}{3}\cos^2\theta_0 - 1\right)$$

Tiny Logic Circuit Elements.—Scientists of the Radio Corporation of America are developing a new type of miniature device that represents an important step toward an ultimate goal of electronic computer components approaching the compactness of those in the human brain, Dr. Irving Wolff, Vice President, Research, RCA Laboratories, announced recently.

Dr. Wolff said application of a new concept of "integrated electronics" has enabled scientists to create a logic circuit element—the basic building block of computers—so compact that up to 100,000,000 such elements might be crammed into one cubic foot. Logic circuits are used in various arrangements in computers to calculate, sort, "remember" and control the flow of information. Present conventional logic circuits employ several types of devices including tubes or transistors as active components to amplify electrical signals, and resistors and condensers as passive components to vary the flow of current.

Dr. Wolff pointed out that in the concept of integrated electronics a complete set of circuit functions, including those of both the active and passive elements, is built into a single extremely small piece of solid material, such as silicon. The new logic element, he said, is an example of this approach.

The application of the integrated electronics concept to a logic system for computers was described by Dr. J. T. Wallmark and Mr. Sanford M. Marcus, who are carrying out the development work. They said that the advent of the transistor, with its small dimensions and low power requirements, already has led to a major advance in electronic techniques of replacing or complementing mental processes, as is done in computers and automation equipment. However, they said, "the ultimate potential of the transistor in this respect has not yet been determined and certainly not yet reached."

Dr. Wallmark and Mr. Marcus emphasized that the means of realizing this potential is the application of the integrated electronics concept, using a device known as a uni-polar transistor in an extremely compact computer logic system.

The two RCA scientists reported that they have now developed and tested in the laboratory an integrated logic element that can be formed of a piece of silicon measuring only .000016 cu. in. By the use of numbers of such elements assembled in various arrays in the manner of a jig-saw puzzle, according to the scientists, all of the functions of present conventional logic elements can be performed without the use of separate components.

They explained that external connections would still be needed between different arrays, as well as to the power supply and the input and output systems. Since the integrated logic system consists of small flat wafers, they said, these connections can be made by simple printed circuits. With this type of construction, the scientists added, extremely versatile assemblies might be built in "sandwich" fashion, with layers of silicon alternating with layers of printed circuits.

They pointed out that continuing research may lead to the use of improved materials other than silicon, such as gallium arsenide and indium phosphide, which have the ability to perform more efficiently at the higher temperatures that would be encountered in densely packed miniature systems.

V.2
195

THE HUMAN OPERATOR AS A SERVO SYSTEM ELEMENT*

BY

DUANE T. McRUER[1] AND EZRA S. KRENDEL[2]

Part II**

Operator Describing Functions in Compensatory Tasks with Controlled Element Dynamics

The next step in a logical development after exhausting the $Y_c = 1$ case would be to delineate the effects upon the operator describing functions due to increasingly complex controlled element dynamics, together with a full coverage of forcing function conditions. Unfortunately a complete experimental basis for such a presentation does not yet exist.

The primary experimental work with controlled elements has been done by Tustin (**18**),[3] Russell (**16**), Goodyear Aircraft (**19–22**), Hall (**23**), and The Franklin Institute (**1**, **17**).

Tustin's study was a pioneering effort, but was quite short and limited in scope. While three different controlled elements were used, they had very similar dynamics in the frequency range of interest. He introduced the remnant concept, presented some information on it, but left the total remnant picture relatively incomplete. Russell's study, which is a logical extension of some of Tustin's notions, considered a progression of increasingly complex controlled element characteristics, with the primary emphasis of the experimental work being placed upon the operator's describing function. Remnant characteristics, in a spectral form, were not thoroughly explored but their effects were revealed to some extent in some cases by total remnant power and error power data. The Franklin Institute F-80 Simulator studies are completely documented in terms of both describing function and remnant characteristics. In these tests the controlled element dynamics were those of an F-80 aircraft and target in a constant range tracking task—by far the most complex situation studied in detail to date. Finally, Hall's data fill in many of the gaps in controlled element characteristic types,

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[1] Systems Technology, Inc., Inglewood, Calif.

[2] The Franklin Institute Laboratories for Research and Development, Philadelphia, Pa.

** Part I appeared in this JOURNAL for May, 1959.

[3] The boldface numbers in parentheses refer to the references appended to Part I of this paper.

and include a survey for conventional short period airframe characteristics. (These latter are not included in the present paper.) His data, being the latest gathered chronologically, include several system parameters not measured previously as well as pilot opinion ratings for the various controlled elements.

The results of fitting these data using criteria similar to those described previously together with other pertinent information, are shown in Tables IV and V.[4] The controlled element transfer functions are

TABLE IV.—*Summary of Operator Describing Functions in Compensatory Tasks with Various Simple Controlled Elements, Random Appearing Forcing Function.*

Controlled Element, $Y_c(s)$	Human Operator Describing Function, $Y_p(s)$	Investigator, Forcing Function, Control Task, and Remarks
$\frac{1}{(s+1)}$	$\frac{20e^{-.15s}\left(\frac{s}{.7}+1\right)}{\left(\frac{s}{.1}+1\right)}$	Russell; Superposition of four sinusoids, $\omega_i = .66$, 1.68, 2.87, and 4.27 rad/sec. Amplitude envelope ≐ 1st order binomial filter with corner at .85 rad/sec; Handwheel control with no restraints
$\frac{1}{\left(\frac{s}{2}+1\right)}$	$\frac{8e^{-.15s}\left(\frac{s}{.9}+1\right)}{\left(\frac{s}{.15}+1\right)\left(\frac{s}{25}+1\right)}$	
$\frac{1}{\left(\frac{s}{.2}+1\right)}$	$\frac{10e^{-.15s}\left(\frac{s}{2}+1\right)}{\left(\frac{s}{3}+1\right)\left(\frac{s}{15}+1\right)}$	
$\frac{15}{(s+1)}$	$\frac{1.5e^{-.2s}\left(\frac{s}{1.5}+1\right)}{\left(\frac{s}{.35}+1\right)}$	Hall; White noise through 3rd order binomial filter with corner at 1 rad/sec. Aircraft handwheel control with spring restraint operated (push-pull) for simulated aircraft longitudinal control, lateral axis Navion aircraft dynamics were controlled simultaneously. Range of measurements .5 rad/sec to 3 rad/sec. Average ρ decreases from .9 to .4 with increasing frequency.
$\frac{15}{\left(\frac{s}{.2}+1\right)}$	$\frac{4.0e^{-.2s}\left(\frac{s}{.4}+1\right)}{\left(\frac{s}{.1}+1\right)}$	
$\frac{15}{\left(\frac{s}{.1}+1\right)}$	$\frac{4.0e^{-.2s}\left(\frac{s}{.3}+1\right)}{\left(\frac{s}{.08}+1\right)}$	
$\frac{1}{s}$	$\frac{3e^{-.15s}\left(\frac{s}{.35}+1\right)}{\left(\frac{s}{.2}+1\right)}$	Russell; Superposition of four sinusoids, $\omega_i = .66$, 1.68, 2.87, and 4.27 rad/sec. Amplitude envelope ≐ 1st order binomial filter with corner at .85 rad/sec; Handwheel control with no restraints.

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[4] The measured points from which the describing function experimental data in Tables IV and V were obtained are in (1).

TABLE IV—*Continued.*

Controlled Element, $Y_c(s)$	Human Operator Describing Function, $Y_p(s)$	Investigator, Forcing Function, Control Task, and Remarks
$\frac{1}{s}$	$\frac{3e^{-.2s}\left(\frac{s}{.3}+1\right)}{\left(\frac{s}{.07}+1\right)}$	Hall; White noise through 3rd order binomial filter with corner at 1 rad/sec. Aircraft handwheel control with spring restraint operated (push-pull) for simulated aircraft longitudinal control, lateral axis Navion aircraft dynamics were controlled simultaneously. Range of measurements .5 rad/sec to 3 rad/sec. Average ρ decreases from .85 to .45 with increasing frequency.
$\frac{5}{s}$	$\frac{1e^{-.2s}\left(\frac{s}{.3}+1\right)}{\left(\frac{s}{.07}+1\right)}$	
$\frac{15}{s}$	$\frac{.6e^{-.2s}\left(\frac{s}{.3}+1\right)}{\left(\frac{s}{.06}+1\right)}$	
$\frac{(s+1)}{s}$	$\frac{120e^{-.2s}\left(\frac{s}{45}+1\right)}{\left(\frac{s}{.05}+1\right)}$	Russell; Superposition of four sinusoids, $\omega_i = .277$, .741, 1.21, and 1.80 rad/sec. Amplitude envelope ≐ 1st order binomial filter with corner at .36 rad/sec; Handwheel control with no restraints.
$\frac{\left(\frac{s}{2}+1\right)}{s}$	$\frac{250e^{-.2s}\left(\frac{s}{20}+1\right)}{\left(\frac{s}{.3}+1\right)}$	
$\frac{5s+10}{5s+1}$	$\frac{K_{\text{high}}e^{-.2s}\left(\frac{s}{.2}+1\right)}{\left(\frac{s}{\omega_{\text{small}}}+1\right)\left(\frac{s}{.6}+1\right)}$	Average $\rho = .7$
$\frac{20s+10}{20s+1}$	$\frac{K_{\text{high}}e^{-.2s}\left(\frac{s}{.15}+1\right)}{\left(\frac{s}{\omega_{\text{small}}}+1\right)\left(\frac{s}{.45}+1\right)}$	Average $\rho = .9$

correct over a wide frequency band, but the human operator describing functions are not, since either several particular frequencies or a narrow band of frequencies were used in their determination. To present the measurements in a more precise context, Tables IV and V also show the controlled element approximate characteristics in the frequency region covered by the human response data. The Goodyear results shown in Table V were actually obtained as an analog computer setup. These have been converted into Gaussian input describing function form to be comparable with the data from other sources.

Tables I through V give a complete summary of the describing function results in mathematical terms. To impart a better appreciation of the effects of controlled element characteristics upon the operator, we

Table V.—*Summary of Operator Describing Functions in Compensatory Tasks with Various Complex Controlled Elements, Random Appearing Forcing Functions.*

Controlled Element, $\frac{Y_c(s)}{K_c}$	Human Operator Describing Function, $Y_p(s)$	Investigator, Forcing Function, Control Task, and Remarks
$\dfrac{1}{\left(\frac{s}{\omega_{ni}}\right)^2+\frac{2\zeta s}{\omega_n}+1}$ $\omega_{n1}=7.8\zeta=.371$ $\omega_{n2}=16\ \zeta=.371$	$Y_{p1}=\dfrac{5e^{-.2s}\left(\frac{s}{7}+1\right)}{\left(\frac{s}{.4}+1\right)}$ $Y_{p2}=\dfrac{15e^{-.2s}\left(\frac{s}{20}+1\right)}{\left(\frac{s}{.2}+1\right)}$	Russell; Superposition of four sinusoids, $\omega_i=.66$, 1.68, 2.87, and 4.27 rad/sec. Amplitude envelope ≐ 1st order binomial filter with corner at .85 rad/sec; Handwheel control with no restraints. Average $\rho_1=.75$.
$\dfrac{1}{s\left[\left(\frac{s}{55}\right)^2+\frac{2(.25)s}{55}+1\right]}$	$\dfrac{200e^{-.15s}\left(\frac{s}{.4}+1\right)}{\left(\frac{s}{.05}+1\right)\left(\frac{s}{2.5}+1\right)}$	Tustin; Superposition of three sinusoids, $\omega_i=.113$, .34, .68 rad/sec for slow input. $\omega_i=.17$, .49, .98 rad/sec for fast input. Simulated tank turret tracking with spade grip handwheel; $Y_c(s)\doteq 1/s$ over the frequency range of measurements. Average ρ =.95. The indicated transfer function does not agree exactly with that given by Tustin.
$\dfrac{\left(\frac{s}{3}+1\right)}{s\left[\left(\frac{s}{20}\right)^2+\frac{2(.8)s}{20}+1\right]}$	$\dfrac{200e^{-.15s}\left(\frac{s}{.4}+1\right)}{\left(\frac{s}{.07}+1\right)(s+1)}$	Tustin; same as foregoing but no ρ estimate was made.
$\dfrac{\left(\frac{s}{1.37}+1\right)}{s\left(\frac{s}{1.67}+1\right)\left(\frac{s}{2.50}+1\right)}$	$\dfrac{.4e^{-.25s}\left(\frac{s}{.3}+1\right)}{\left(\frac{s}{5}+1\right)}$	Goodyear (19); Superposition of four wave shapes such that the forcing function was roughly equivalent to white noise through a 3rd order binomial filter with corner at 2 rad/sec. Longitudinal control of simulated aircraft, stick with spring restraints. Describing function is an approximation to an analog computer set up.
$\doteq\dfrac{\left(\frac{s}{1.4}+1\right)}{s\left(\frac{2}{2.4}+1\right)\left[\left(\frac{s}{4.2}\right)^2+\frac{2(.52)s}{4.2}+1\right]}$	$\dfrac{K_pe^{-\delta s}\left[\left(\frac{s}{\omega_n}\right)^2+\frac{2\zeta s}{\omega_n}+1\right]}{(T_Ns+1)}K_T\left[\frac{a_T}{\sigma_T}\right]$	Goodyear (20); White noise through 1st order binomial filter with corner at .33 rad/sec and then through another 1st order binomial filter with corner frequency at ≐ 4 rad/sec. Longitudinal control of simulated aircraft, moving base pitching simulator, stick with inertial spring and damping restraints. Describing function form is an approximation from an analog computer setup.

V.2
195

TABLE V—*Continued.*

Controlled Element, $\frac{Y_c(s)}{K_c}$	Human Operator Describing Function, $Y_p(s)$	Investigator, Forcing Function, Control Task, and Remarks
$\doteq \frac{\left(\frac{s}{.24}+1\right)\left(\frac{-s}{2.9}+1\right)}{s^2\left(\frac{s}{.0017}+1\right)}$	$\frac{.2e^{-.15s}\left(\frac{s}{.2}+1\right)}{\left(\frac{s}{2.5}+1\right)\left(\frac{s}{10}+1\right)}$; $\omega_{co}=1$ rad/sec $\frac{.3e^{-.15s}\left(\frac{s}{.3}+1\right)}{\left(\frac{s}{3}+1\right)\left(\frac{s}{10}+1\right)}$; $\omega_{co}=2$ rad/sec $\frac{.5e^{-.15s}\left(\frac{s}{.2}+1\right)}{\left(\frac{s}{1.5}+1\right)\left(\frac{s}{10}+1\right)}$; $\omega_{co}=4$ rad/sec	Franklin Institute (1); White noise through 3rd order binomial filter giving 3 available corner frequencies, $\omega_{co}=1$, 2 and 4 rad/sec; Lateral control of simulated aircraft in tail chase, stick with spring restraints. Longitudinal axis was under simultaneous control. Range of measurements .6 to 3.6 rad/sec. Average $\rho \doteq .5$.
$\frac{\left(\frac{s}{.28}+1\right)\left(\frac{s}{1.58}+1\right)}{s^2\left[\left(\frac{s}{3.98}\right)^2+\frac{2(.56)s}{3.98}+1\right]}$	$\frac{.6e^{-.15s}\left(\frac{s}{4}+1\right)}{\left(\frac{s}{40}+1\right)\left(\frac{s}{10}+1\right)} \doteq .6$; $\omega_{co}=1$ rad/sec $\frac{.6e^{-.15s}\left(\frac{s}{6}+1\right)}{\left(\frac{s}{20}+1\right)\left(\frac{s}{10}+1\right)} \doteq .6$; $\omega_{co}=4$ rad/sec an equalizing form fit; $\omega_{co}=4$ rad/sec was not achieved.	Franklin Institute (1); Same forcing function and range of measurements as above, different stick spring loading. Longitudinal control of simulated aircraft in tail chase. Lateral axis under simultaneous control. Average $\rho \doteq .6$, A sgn function was an equally good fit to that indicated for $\omega_{co}=1$ and 2 rad/sec, and $Y_p = .6e^{-.25s}$ was "best" fit for $\omega_{co}=4$ rad/sec.

can make some general comments and observations on some of the data for the three simplest controlled element configurations.

1. Effect of Gain Changes in Controlled Element; $Y_c = K_c$. For a given forcing function the effect of gain changes in the display or the control, either during a run or from run to run, is almost entirely compensated for by the operator, who tends to set his gain in such a way as to hold the over-all loop gain at some given value. Slight changes in over-all loop gain can be effected by changes in the display gain, but nowhere near the amount that would occur had the operator held his gain constant. An increase in loop gain can be the result of instructions to "put more into it" or "try harder."

2. Effects of Insertion of a Simple Lag; $Y_c = 1/Ts + 1)$. When simple lags are placed into the control loop the operator's transfer characteristics change to a marked degree. In all cases the major effects were the operator's development of a lead term in a fashion tending to compensate for the introduced lag, a reduction in gain, and probably a change in his first lag time constant.

The following should also be noted:

a. When the lag time constant was smaller than about 0.05 second, the inserted lag had no effect on the describing function. In addition, the operator could scarcely notice the effect of the inserted lag on his stimulus.

b. As the controlled element time constant was increased above 0.05, the operator could detect a distinct sluggishness in the system. This became more and more prominent until values of controlled element lag time constant, T, of 2 seconds or larger were used, when the controlled element appeared to the operator to take on the characteristics of a pure integrator.

c. When lags are initially inserted into the loop the operator tends to overshoot somewhat, occasionally to the point of system instability, until he acquires some practice. After practice for a minute or so, he adapts his characteristics to suitable values for stability.

d. The reduction in loop gain when the lag is inserted is larger than required to maintain stability.

V.2
195

3. Effect of Insertion of Pure Integration; $Y_c = K_c/s$. With a controlled element consisting of a simple pure integrator the operator lowers his gain and introduces a lead which generally tends to compensate for the $e^{-\tau s}$. This change allows the over-all system to be stable, but is also in the direction to increase the mean square tracking error over that with no controlled element dynamics. The closed loop low frequency response is improved because of the higher over-all system amplitude ratio at low frequencies due to the s^{-1} term. With a change in K_c, the operator modifies his gain to keep the crossover frequency (or open loop gain) substantially constant.

Operator Remnant Data

By definition, the remnant is that portion of the operator's output which is not linearly coherent with the forcing function, that is, which cannot be "explained" as the result of a linear operation on the system input. Since most of the available data were taken for random appearing forcing functions, it is convenient to express the remnant in terms of a power spectral density, Φ_{nn}. In a given situation, components of Φ_{nn} could result from the following sources:

1. Operator responses to inputs other than the supposed system forcing function. These responses could exist in two categories,

a. The result of a linear operation by the operator on these other inputs.

b. The result of nonlinear operation on these inputs.

2. Nonlinear operation by the operator on the forcing function. The portion of the remnant due to this source would be coherent with the forcing function by some nonlinear correlation.

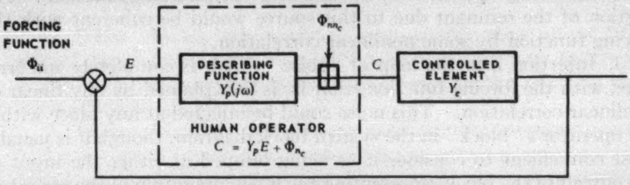
3. Injection into the loop of "noise" which is completely uncorrelated with the forcing function, that is, is unexplained by any linear or nonlinear correlation. This noise could be injected at any place within the operator's "block" in the system block diagram, though it is usually most convenient to consider it as being lumped at either the input or the output of the block representing the linear operation of the operator.

4. The variation, during a measurement run, of the operator's linear transfer characteristics. By necessity, the describing function is found experimentally by the use of fairly long runs, for example, 2 to 4 minutes. In particular portions of these runs the operator may be responding in one linear fashion which is changed to various other linear modes of behavior during other portions of the run, or he may be varying his characteristics almost continually over much shorter intervals. The measured describing function is, of course, a particular kind of "average" of all these characteristics, and hence cannot "explain" all of the actual output power. This type of behavior shall be termed "nonsteady."

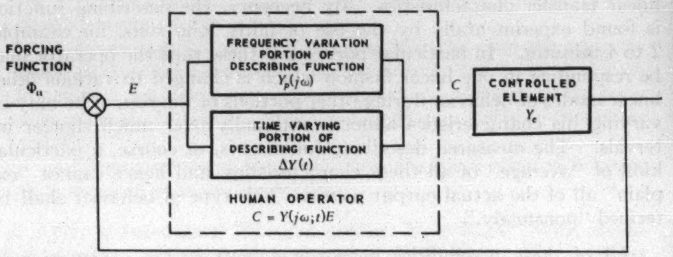
All of these possibilities have some merit in the explanation of existing remnant data. Hall has shown that the first source offers an appropriate explanation for a portion of the remnant when two dimensional system inputs are present, that is, crosstalk through the operator. The remaining remnant in multi-input tasks and the total remnant in single input cases, must be due to the last three possibilities, either singly or in some combination. Unfortunately, present data do not allow us to ascribe partial responsibility for the remnant to any one source. Accordingly, we have derived a series of possible remnant "models" where each source is assumed as an all inclusive explanation for the total remnant. While the details of the analysis are beyond our present scope, we can summarize the various remnant models so far derived, and can also indicate their consequences in terms of operator description (Fig. 5).

A. Noise Injection Models

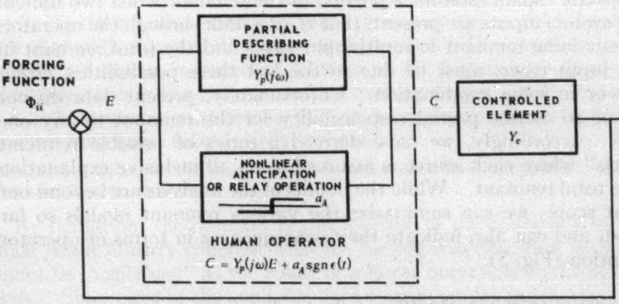
1. Input Noise Injection. The possibility of errors in the visual sensor (or other location near the operator's input), being responsible for a portion of the remnant does exist, but it is difficult to develop an *a priori* model which can be used as a basis for fitting the observed remnant data. However, the remnant data obtained from the measurements made by Elkind and The Franklin Institute were converted to a form consistent with the assumption of input noise injection, and then examined for trends which might suggest some suitable model. This procedure did not result in any clear-cut findings, although it was noted that the remnant from Elkind's rectangular spectra forcing function tests, to a value of f_{co} of 0.64 cps, could be represented quite well by an equivalent "white noise" injected at the input.


FORCING FUNCTION
Φ_{ii}
E
DESCRIBING FUNCTION
$Y_p(j\omega)$
Φ_{nn_c}
C
CONTROLLED ELEMENT
Y_c
HUMAN OPERATOR
$C = Y_pE + \Phi_{n_c}$

a. Output Noise Injection Remnant Model.


FORCING FUNCTION
Φ_{ii}
E
FREQUENCY VARIATION PORTION OF DESCRIBING FUNCTION
$Y_p(j\omega)$
TIME VARYING PORTION OF DESCRIBING FUNCTION
$\Delta Y(t)$
C
CONTROLLED ELEMENT
Y_c
HUMAN OPERATOR
$C = Y(j\omega; t)E$

b. Nonsteady Operator Behavior Remnant Model.


FORCING FUNCTION
Φ_{ii}
E
PARTIAL DESCRIBING FUNCTION
$Y_p(j\omega)$
NONLINEAR ANTICIPATION OR RELAY OPERATION
a_A
C
CONTROLLED ELEMENT
Y_c
HUMAN OPERATOR
$C = Y_p(j\omega)E + a_A \operatorname{sgn} \epsilon(t)$

c. Linear With Parallel Sgn Function Operator Description.

Fig. 5. Possible forms of the operator model.

V.2
195

2. Output Noise Injection. This remnant source possibility is represented by Fig. 5*a*, in which a "noise" or error is superimposed upon the operator's linear output, and effectively injected into the system. An *a priori* model of sorts (1, 15) can be derived for this possibility based upon the assumption that the human's output response, $c(t)$, can be approximated by a series of discrete steps. Each step would then consist of two components, that is,

a. A part linearly related to the forcing function;

b. A part, $n_e(t)$, representing random error or noise, which is not linearly coherent with the forcing function, and which is independent of all other output steps.

The mathematical consequence of these assumptions is that the output injected noise will have a spectral density given by:

$$\Phi_{nn_e} = 2T\sigma_{n_e}^2 \left[\frac{\sin\frac{\omega T}{2}}{\frac{\omega T}{2}}\right]^2, \qquad (18)$$

where T is the average time between the incremental output steps, and $\sigma_{n_e}^2$ is the mean square value of the injected noise. If this form of equation is used to curve fit Elkind's rectangular forcing function spectra data, one finds that, while the curve fits are not as precise as might be desired, the general form is suitable to define the trends. These indicate that, if this remnant model is accepted, the time between output step increments would have to increase directly, and the mean square noise decrease slightly, with an increase in forcing function bandwidth.

B. Nonsteady Operator Behavior Models

This concept is based on the notion that the operator's transfer characteristic is essentially linear but time-varying in some random fashion which is not linearly coherent with the forcing function (1). While there is no *a priori* model available, the Elkind closed loop remnant data, if interpreted as arising from a time-varying part of the closed loop transfer function, $\Delta H(t)$, are closely fitted with a $\left[\frac{\sin\frac{\omega T}{2}}{\frac{\omega T}{2}}\right]^2$ curve. These fits imply that, if nonsteady behavior is the primary remnant source, the random time-varying portion of the closed loop transfer function, $\Delta H(t)$, would possess a boxcar-like time structure. Its mean square value would increase almost directly with the forcing function bandwidth, and the time between steps in a time history of $\Delta H(t)$ would average about 0.25 second. The equivalent open-loop time-varying characteristic, $\Delta Y(t)$, would have an rms value not so drastically dependent upon the forcing function characteristics and may possibly be nearly constant. Such a nonsteady transfer characteristic will act in parallel with a describing function which is frequency variant only, as shown in Fig. 5*b*.

C. Nonlinear Transfer Characteristic Model

In both the Elkind and Franklin Institute data there is little change in the describing function measurements with variable input amplitude. This fact indicates that, within the range of the conditions tested, a series nonlinearity is not an important effect. On the other hand, the Goodyear analog required the use of a threshold element in series with the linear elements of the system. This threshold was considerably larger than that which could be ascribed to perceptive thresholds, etc., and apparently was due to the operator's indifference, or tendency to ignore signals below some small level. The small variations in describing function that were present in Elkind's results are consistent with the existence of this threshold. The over-all effect, however, is so small that it cannot be considered to be an important remnant source.

A nonlinear element in parallel with the linear describing function, however, is a different matter. The Goodyear analog required just such an element to obtain a good correspondence between the actual and analog operator. The form used there was an anticipation, or sgn function operating in parallel with the quasi-linear describing function (Fig. 5*c*). If the describing function of the parallel sgn or perfect relay function is small relative to that of the quasi-linear describing function, then the main response contribution of the perfect relay will be the remnant. Further, the remnant time history will be of the boxcar-like rectangular nature already noted as a consequence of the output noise injection and nonsteady operator remnant models. For the specific forcing function used by Goodyear, the values of average times between increments check nicely with those required by these previous conceptions. Also, most of the Elkind rectangular spectra forcing function remnant data can be accounted for by the assumption of a sgn function.

V.2
195

The Franklin Institute F-80 Simulator remnant data are, unfortunately, severely contaminated with controlled element effects and were measured over a band of frequencies which is not properly placed either to validate or invalidate the three remnant models discussed above. In general, however, the Franklin data are consistent with all three models. Also, in the case of longitudinal control, the operator describing function can be expressed fairly well as a pure gain for corner frequencies of 1 and 2 radians per second. For input cut-off frequencies of 1 and 2 radians per second, this is exactly the behavior that would be expected for those tasks where the describing function of a simple, parallel nonlinearity is larger than the quasi-linear frequency variant describing function. The linear correlation was somewhat higher for a corner frequency value of 4 radians per second, and for this case the phase characteristic of Y_p can be simply approximated by $e^{-0.25s}$, the sgn function being less dominant. The F-80 Simulator longitudinal control task case exhibited a higher linear correlation than the corresponding lateral control task, but both were the lowest linear correlations for all tasks considered in this paper.

In addition to the major remnant characteristics discussed above, a dither phenomenon observed in the Goodyear tests must also be considered to be a possible human output under certain conditions. The dither action is analogous to that used in servo systems as a linearizing technique, for example, to reduce the effects of coulomb friction. Besides appearing in the Goodyear tests it has also been observed in human dynamics experiments where such a technique appeared to the operator to be an applicable tactic. In all cases it is a conscious action, and can be eliminated by the operator if desired. For the data we have reviewed here

1. No dither was present in Elkind's test, probably because there were no restraints whatsoever upon the control.
2. Dither was probably present in some of Russell's runs, since a sharp peak at 1.23 cps was found on the only remnant spectrum measured. Russell's control wheel spoke was attached directly to an instrument having a fairly high coulomb friction level, so dither might have been desirable.
3. In The Franklin Institute test series several of the subjects tried out the use of a dither signal during their training periods, but abandoned it before their record runs were taken. This was done not because dither introduction was an unsuitable technique for operating the simulator, but because these pilots did not consider it to be part of their normal piloting style.

HYPOTHETICAL MODEL OF THE HUMAN OPERATOR IN COMPENSATORY TRACKING TASKS

From the data presented in Tables I through V we shall endeavor to hypothesize a reasonable model of the operator. In constructing the hypothetical model, the transfer characteristics will be considered first, on a term-by-term basis.

A. Hypothetical Transfer or Describing Function Model

1. Reaction Time Delay. The reaction time delay, represented by an $e^{-\tau j\omega}$ term, appears in all operator transfer functions which are subjected to forcing functions having a degree of unpredictability or "randomness."[5] Also, it is probable that an $e^{-\tau j\omega}$ term is present in all tracking tasks in which the operator's input is random-appearing, although the line of demarcation on a phenomenal level between random appearing and predictable inputs is not well defined at present. For instance, the use of a perfectly predictable sine wave forcing function on a system with an operator plus complex controlled element dynamics, resulting in a complex, nonsinusoidal error signal (operator input), probably falls into the random appearing input class. In the same case, reduction of the controlled element dynamics to some simpler (but presently unknown) form would tend to preserve the predictable sinusoidal wave form, and the operator input would then fall into the predictable class.

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[5] With the possible exception, noted previously, of the Franklin F-80 Simulator longitudinal runs.

When the simplest of the fitted transfer function forms is used to derive a value for τ, a considerable variation in this initially determined pure time delay is apparent. Then, when a stability requirement is asserted, and stability of the fitted form is obtained by the introduction of a high frequency lag beyond the bandwidth of measurement, the resultant τ values appear to lie within a relatively small grouping, with a central value of about 0.15 second for random appearing visual inputs. There also appears to be a fairly steady progression of decreasing τ values from about 0.25 second for widely separated step inputs, to about 0.20 second for more closely spaced and random appearing discrete steps (see Table I) and finally to the 0.15 second cited above for random appearing forcing functions. On both single-input, single-output systems and two-input, two-output systems with random appearing forcing functions, τ does not appear to be a distinct function of either forcing function alone or controlled element characteristics alone. Whatever variability does exist in values of τ appears to be on an intrasubject basis. It is probable that these variations are similar in both scope and form to those found in applicable reaction time experiments to discrete stimuli, since τ is certainly closely related to classical reaction time lags.

The hypothetical linear model for continuous control, visual input, compensatory tasks should, then, always include an $e^{-\tau j\omega}$ term in the describing function to account for the reaction time delay, with τ given approximately as

$$\tau \doteq 0.15 \text{ second}. \qquad (19)$$

2. *Neuromuscular Lags.* The dynamic portion of the data from step forcing functions for $Y_c = 1$ (Table I) and that obtained for the nonsynchronous phases of sine wave forcing functions for $Y_c = 1$ (Table I) have a fair degree of similarity, and are presumably indicative of the actuator (neuromuscular) portion of the human response. The neuromuscular system involved in the particular measurements was that of the arm in following, and the describing numbers would be somewhat different for other neuromuscular systems. This actuator

V.26
1959

portion of the human response is not directly apparent in the other describing function data since the effect would be minor at the frequencies used for determining them. It will be recalled, however, that much of the data required, as a minimum, the addition of a high frequency lag (beyond the measurement bandwidth), to stabilize the system.

We should also note that Elkind's higher forcing function bandwidths will scarcely admit of very large values for neuromuscular lags (because they would have to be subtracted from the already small values of τ), unless they are associated with the very low frequency lag break point probably present; or unless both a lead and lag exist beyond the measurement bandwidth. The evidence for the second possibility is mixed, and the possibility of the low frequency lag being truly due to the neuromuscular system is extremely unlikely.

Since much of the evidence available at the higher frequencies (particularly those from step function inputs), indicates the existence of neuromuscular lags, and most of the other data implies their probable presence, a hypothetical model of the operator should include the effect. If really due to the neuromuscular system, these lag terms should be at least of the second order variety but the only numerical value that one can derive from the random input tracking data is a first approximation consisting of a first order lag.

3. *Indifference Threshold.* The "indifference threshold" effect used by Goodyear, and compatible with Elkind's variable amplitude data, does appear to exist. This serial effect should therefore be taken into account, at least in principle. This can be done by using a threshold describing function, $K_T\left(\frac{a_T}{\sigma_T}\right)$, in series with the other elements of the transfer function. As a Gaussian input describing function this is given approximately by,

$$K_T\left(\frac{a_T}{\sigma_T}\right) = 1 - \Phi\left(\frac{a_T}{2\sigma_T}\right) + \sqrt{\frac{2}{\pi}}\frac{a_T}{\sigma_T}\, e^{-(a_T/\sqrt{2}\sigma_T)^2}$$

$$\doteq 1 - 2\sqrt{\frac{2}{\pi}}\frac{a_T}{\sigma_T}; \quad \frac{a_T}{\sigma_T} \ll 1, \qquad (20)$$

where a_T is the value of the threshold, σ_T is the rms value of the operator's input signal, and $\Phi(x)$ is the error function. Equation 20 has only a slight change from unity for the relatively small values of $\frac{a_T}{\sigma_T}$ observed. It can therefore be considered as a minor effect for the cases covered by present data.

4. *Equalization.* A most important item to be considered in any transfer function form is the equalizing ability of the operator. This is shown by the presence on occasion of: first order lead, low frequency

first order lag, and the probable existence of a variable high frequency lag (which may be part of the neuromuscular system).

Considering only those experimental studies in nonmoving mockups with pure visual inputs, a single low frequency lag term *always* appears to be present when all of the following conditions apply:

a. When the introduction of a low frequency first order lag would improve the low frequency system response;

b. When the low frequency system response is important because of the low bandwidth of the input;

c. When the controlled element characteristics are such that the introduction of the low frequency lag will not result in higher frequency destabilizing effects incapable of being overcome by a single first order lead.

When these conditions do not apply, the low frequency lag does not appear.

When the controlled element characteristics, coupled with the "unalterable" reaction time delay term of the operator, are such that a lead term would be desirable from either a system stability or low frequency system performance standpoint, then the operator will generate a first order lead.

Either a second low frequency lag or a second lead term is difficult for the operator to generate when confronted with only visual, random appearing inputs and controlling relatively simple controlled element configurations (those of Tables II–IV). Several of the systems studied could have used such terms to advantage and there is no conclusive indication of their existence.

There are, however, instances in systems with more complex dynamics where experienced trackers have generated a second order lead for system stability. Also, a second order lead appears to be possible under special circumstances. For example, some highly trained Navy jet pilots used as subjects by Goodyear were able to generate quadratic lead terms while operating in a moving simulator (Table V).

Expressed mathematically, the operator's equalization characteristic, with only visual inputs, can commonly assume the following forms:

$$\begin{aligned}
&K_p\frac{\alpha T_I j\omega + 1}{T_I j\omega + 1} && \alpha > 1 \text{ (lead-lag)} && (a)\\
&K_p\frac{\alpha T_I j\omega + 1}{T_I j\omega + 1} && \alpha < 1 \text{ (lag-lead)} && (b)\\
&K_p(T_L j\omega + 1) && \text{(simple lead)} && (c) \qquad (21)\\
&\frac{K_p}{T_I j\omega + 1} && \text{(simple lag)} && (d)\\
&K_p && \text{(pure gain)} && (e).
\end{aligned}$$

V.2
195

This ability to adapt the *form* of the frequency variant equalizing characteristic can be referred to as the *adaptive* behavior of the operator.

We should note that the final transfer function obtained in a given task is a strong function of the operator training in the particular control task. All of the describing function data considered in this series were valid *after* the learning period. Therefore, adaptive behavior refers to what the operator can do after he has achieved some familiarity with the particular control process. The length of the trial and error process involved in achieving the final transfer function form is, of course, quite dependent upon the forcing function and controlled element characteristics and the background of the operator. For example, in Russell's tests only seconds or fractions thereof were required to adapt properly for variations in controlled element characteristics during a run; much longer times were required on The Franklin Institute F-80 Simulator simply to achieve familiarity with the simulator, even with skilled pilots as subjects. Goodyear stated that as much as 20 hours was required by one of their subjects (a non-pilot) before he attained any reasonable degree of proficiency in controlling the simulator.

5. Gain Adjustment and Optimalizing Behavior. From all of the data it is apparent that operator gain is a highly adjustable parameter. It also appears to be a distinct function of individual motivation and training in the particular task.

In addition to gain adjustment, all the evidence available indicates that the operator is not only *adaptive* in selecting the form of his equalization function within the rough limits set above, but also adjusts the value of some of the constants within the transfer function adapted. Some insight into this behavior can be obtained by considering the simple tracker data as a function of forcing function bandwidth. From the Franklin simple tracker (Table II) it appears that the lead time constant, T_L, is considerably reduced as the bandwidth is increased, indicating that the operator is attempting to increase his bandwidth as the presented information requires such an increase. A similar trend is seen in the Russell and Elkind data, except that there the operator changes his low frequency lag time constant and gain, for example, $K \doteq 9.42 T_I$ for Elkind's data. Both of these characteristics show a distinct tendency on the part of the operator to adjust his parameters in an endeavor to follow the forcing function and to minimize the effects of other signals present in his input.

This behavior is similar to that expected of an "optimalizing" servo system, that is, one that adjusts the values of its constants to some optimum operating condition as a function of its inputs. It can then be said that the human operator is both "adaptive" (within a relatively fixed form), and "optimalizing" (to some difficult to define criterion). In fact, the human operator is the very prototype of an adaptive, optimalizing servo system.

While the actual internal criterion of the human defies definition, we can obtain considerable insight into the consequences of its operation. Figure 6 summarizes all available phase margin (180 degrees minus open loop phase when open loop gain is unity) data for cases where measured describing function points occur in the region of gain crossover. The phase margins shown were read from the actual data joined point to point, so they do not necessarily agree precisely with phase margins deduced from the analytical curve fits. These data indicate that gain and equalization, as finally adjusted, are such that phase margins in the region of 60 to 110 degrees occur. These values of phase margin are very similar to those which might be used by a servo designer.

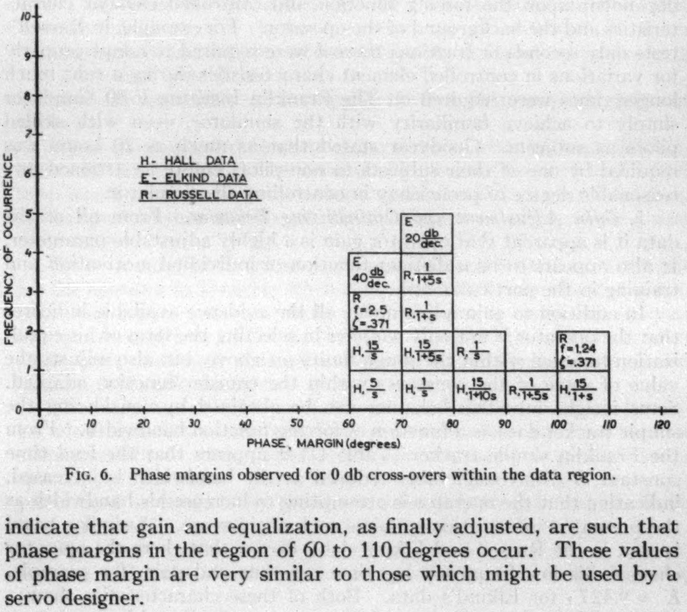

FIG. 6. Phase margins observed for 0 db cross-overs within the data region.

In summary it appears that the operator adjusts his parameters as some function of his presented input. Further, he tends to modify his transfer characteristics until he has achieved either a performance level which he accepts or, perhaps, a level which represents the limit of his abilities. It should be pointed out that the phase margin data of Fig. 6 tend to support the first of the possibilities, while operator action tending to create the second was generally requested by the experimenter. Other experimental conditions, for example, when the operator is asked to keep his signal within a rigidly defined set of limits shown on the display, may not yield similar results to those given here.

V.2
195

6. Hypothetical Transfer Function Model. From all of the above it is now possible to hypothesize a linear adaptable model of the human operator for random appearing visual inputs and motion outputs, which is consistent with all of the data available. In equation form:

$$Y_p = \frac{Ke^{-\tau j\omega}(T_L j\omega + 1)}{(T_I j\omega + 1)(T_N j\omega + 1)} K_T \left(\frac{a_T}{\sigma_T}\right)$$

$$= \frac{K_p e^{-\tau j\omega}(\alpha T_I j\omega + 1)}{(T_I j\omega + 1)(T_N j\omega + 1)} K_T \left(\frac{a_T}{\sigma_T}\right), \quad (22)$$

where

Reaction time delay, τ, is: $0.12 < \tau < 0.20$ second.

Neuromuscular lag, T_N, is partially adjustable for task.

Equalization, $\frac{(\alpha T_I j\omega + 1)}{(T_I j\omega + 1)} = \frac{(T_L j\omega + 1)}{(T_I j\omega + 1)}$, is adjustable with forcing function and controlled element.

Gain, K_p, is adjustable for over-all system stability and low frequency performance.

Indifference threshold, $K_t \left(\frac{a_T}{\sigma_T}\right)$, is a minor effect with adjustment and values not known.

Within the limitations of the above form the operator adapts his transfer function (lag-lead, lead-lag, pure lead, pure lag, or pure gain) to obtain what he considers to be an optimum controller, controlled-element system response in the presence of the forcing function. The transfer function form adapted is one consistent with stability and good low frequency control of the over-all system. The constants are adjusted to some performance criterion akin to that of the rms minimization criterion of servo theory, and consistent with phase margins from 60 to 100 degrees. In other words, *the operator transfer function for a given task is very similar to the one that a servo engineer would select if he were given an element to control together with a "black box," having within it elements making up the describing function given by Eq. 22 and knobs on the outside for adjustment of* α, T_I *and* K_p.

B. Hypothetical Remnant Models

Three models have been proposed to "explain" that portion of the operator's output which is not "linearly coherent" with the system forcing function in single dimensional tasks. The analytical form and general consequences of these various possibilities are illustrated in Fig. 5 in the preceding section.

There is little to choose among these three conceptions. In terms of the existing data on operator uncorrelated output power, all three are effectively equivalent models. In addition, all "explain," to some extent at least, the quasi-periodic behavior observed on time records of human responses.

When more detailed factors are examined, such as the point-by-point output check between the Goodyear analog and actual pilots, the perfect parallel relay description (derived from the Goodyear studies), becomes very enticing. Unfortunately, this description is based upon only one set of controlled-element, forcing-function characteristics. The other remnant data could be explained to a large extent by such an "anticipation" model (and vice-versa, of course), but a limiting case tends to make us wary of the outright assertion that this is the best model. This limiting condition will occur when the operator's task is very demanding, so that the parallel, nearly linear, describing function is very small relative to $K_A\left(\frac{a_A}{\sigma_\epsilon}\right)$, the describing function of the sgn transfer characteristic. Under these conditions, the over-all operator describing function would tend to be a pure gain, with no reaction time delay. This was the case for the Franklin F-80 Simulator longitudinal data, but did not exist for the lateral case where only 25 per cent or so of the output power is described by the linear operations.

V.2
195

In view, therefore, of the limitations on the data, there is insufficient justification to prefer one remnant form over the others, exclusively. However, the following comments upon the features of each of the models might be noted:

1. The nonsteady model is "best" from the point of view that the curve fits upon which it is based were the most adequate ones made;
2. The noise injection model is "best" from the standpoint of simplicity in using the hypothetical transfer function data for system stability predictions and general servo analysis;
3. The parallel sgn function, or perfect relay, model is "best" for point-by-point prediction of the operator's output and in creating an intuitive physical view of the operator's actions.

Because of the approximate equivalence of the three models, and the points enumerated above, we feel that an eclectic view is the most practical at the present level of data development. By accepting this viewpoint, the choice of a remnant model is left to the engineer or psychologist analyzing a particular job at hand. Of course, due caution and restraint should be used in not exceeding the bounds imposed by the experimental conditions for which the models were originally derived.

Some general factors regarding the remnant and linear correlation should also be noted. In brief, for a forcing function other than zero, these are:

1. The highest linear correlation coefficient is associated with least rms tracking errors.
2. Since highest values of ρ correspond to the least remnant, minimum rms errors are associated with the least remnant.
3. The smallest remnant is associated with controlled system elements having minimum dynamics ($Y_c \doteq 1$).
4. The least remnant is associated with operator inputs having the least bandwidth.

PREFERRED OPERATOR FORM IN COMPENSATORY TASKS—THE DETERMINATION OF "IDEAL" MANUAL CONTROL SYSTEMS

In preceding sections consideration was given to the performance of the operator in particular tasks, and an adaptive, optimalizing model was hypothesized to characterize his behavior. This model can be used with some confidence to predict the qualitative performance of a given man-machine system. While useful in an analysis problem it is desirable, for synthesis purposes, to know how the operator should perform if the manual control system is made ideal based upon some system performance criterion. Further, if the "ideal" system is also the most practical one from an over-all standpoint, how do we make the human behave that way?

To derive a performance characteristic which is presumably the "best" for the operator to adopt we can use data of two varieties. The first, of course, are the describing function and remnant data previously summarized. From these data we can draw some conclusions about those controlled element and forcing function conditions which tend to be more desirable than others from the standpoint of over-all system performance.

The second form of data giving us clues in finding preferred operator characteristics is the experimental determination of some system performance measure, such as rms error, time on target, etc., as a function of controlled element and forcing function conditions. This latter approach, emphasizing particularly the controlled element characteristics, has been used extensively by Birmingham and Taylor and their colleagues (**24–28**). As a result of their efforts using this approach, they hypothesized a preferred form of operator behavior which is discussed in detail in References 24 and 25. Many aspects of the Birmingham-Taylor design recommendations still appear applicable.

In preceding parts of this paper it was pointed out that the human operator can be represented by the following, more or less equivalent, general forms:

$$C(j\omega) = Y_p(j\omega)E + N_c(j\omega)$$

or

$$C(j\omega) = Y_p(j\omega; t)E \tag{23}$$

or

$$C(j\omega) = Y_p(j\omega)E + a_A \operatorname{sgn} \epsilon\ (t).$$

On a closed loop basis all of the above forms can be put into quantities which are more easily measured (at least by the quasi-linear methods), and which, in this sense, are more fundamental. Thus, repeating Eq. 13, the output power spectral density is

$$\Phi_{cc} = |H|^2\Phi_{ii} + \Phi_{nn} \tag{24}$$

and the error spectral density is

$$\Phi_{\epsilon\epsilon} = \frac{|H|^2}{|Y_p|^2}\Phi_{ii} + |Y_c|^2\Phi_{nn}. \tag{25}$$

The components of the $|H|^2\Phi_{ii}$ term in Eq. 24, that is, the open loop describing function Y_pY_c, and the forcing function spectral density Φ_{ii}, are of major importance in determining system stability and dynamic performance. While both the linear $\left(\frac{|H|^2}{|Y_p|^2}\Phi_{ii}\right)$, and remnant terms $(|Y_c|^2\Phi_{nn})$, of Eq. 25 are important components of the error spectral density $\Phi_{\epsilon\epsilon}$, the portion due to the remnant is ordinarily the major contributor to $\Phi_{\epsilon\epsilon}$. Since tracking precision is related directly to the error spectrum, for example, $\overline{\epsilon^2} = \int_0^\infty \Phi_{\epsilon\epsilon}df$, the reduction of the remnant, Φ_{nn}, is a major key to precision of performance.

If an "optimum" manual control system is defined as one where the error spectrum is minimized in some sense, while maintaining adequate stability and control, then this implies that the remnant should also be close to a minimum value. Since the remnant is dependent upon the open loop describing function, then an "optimum" form of operator describing function, Y_p, can be said to be that which tends to minimize Φ_{nn}. The operator describing function is, of course, dependent upon forcing function and controlled element characteristics. If a preferred operator form could be found, then these qualities could be adjusted to obtain the operator's describing function preferred form.

It is evident that controlled element transfer characteristics and forcing function conditions are the major non-subjective definition of task difficulty. It is also apparent that the more "difficult" either or both of these characteristics become, the larger the remnant. All of this can be cited as evidence of the fact that the operator is best when subject to the weakest demands. This leaves us with the problem of defining what "weakest demands" means. When this has been done, a rational design scheme can be promulgated which will allow the human to generate the characteristics which yield best system performance.

Both of these problems, that is, first defining a "doing least" operator transfer characteristic form and then a consequent rational design procedure, have been attacked by Birmingham and Taylor. In the words of Reference 24:

> It becomes, therefore, a fundamental assumption . . . that the more complex the human task, the less precise and the more variable becomes the man. It is assumed that, within limits, the higher the number of integrations and/or differentiations required of the man the poorer will he perform. Conversely, it is hypothesized that the more the human operator is freed from the tasks of integration and differentiation the more regular and precise will become the human output. Human control behavior, it is asserted, reaches the optimum when the man becomes the analogue of a simple amplifier (with pure time delay) as shown in the following equation:
>
> $$\theta_0(t + \tau) = K\theta_i(t)$$
>
> or in Fourier transform style (26)
>
> $$\theta_0(j\omega) = Ke^{-\tau j\omega}\theta_i(j\omega)$$
>
> where t represents a value in time, and τ equals the human reaction time.

The Birmingham-Taylor thesis quoted above is given some support in Reference 26. Reported there are the results of a series of tests where the operator is provided with instantaneous knowledge of the effects of his own motions in such a way as to make it unnecessary for the operator to generate either a lead term or an integration. In the actual experiment, the controlled element proper had a transfer function K/s^3. The effective controlled element, as seen by the operator, could be adjusted by equalization techniques to take the form $\dfrac{K(T_1s+1)(T_2s+1)(T_3s+1)}{s^3}$ or remain in its original form, K/s^3. In this experiment a four-coordinate tracking task was employed. The operator manipulated two joysticks to keep two targets within view on a two-gun cathode ray tube. Each target dot was free to move in both the vertical and horizontal directions. No specific forcing function was used, although system noise and extraneous operator motion were sufficient to excite the target.

The results of these tests show, that with the lead terms added to the controlled element, a majority of the operators were able to perform the task perfectly. In the absence of the lead terms, these same operators were never able to control the dot in two dimensions, though some learned, over a period of time, to exert sufficient control of the dot in one coordinate to increase their score materially.

This experiment indicates the general effect of providing sufficient external equalization to allow the operator to function as a simple amplifier and pure time delay (though whether he actually did precisely this is not known, since describing functions were not measured). It therefore adds to that considerable body of data taken on specific tracking, fire control, flight control systems, etc., where "aided tracking," "quickening," "null steering," "zero reading," etc., terms (similar in their effect to the leads introduced here) are employed to improve precision of control. These experiments all tend to justify (or at least not contradict) the Birmingham-Taylor hypothesis advanced earlier that the operator should be allowed to operate with a transfer function $Ke^{-\tau s}$. It is appropriate to discuss possible modifications to the approach in the light of the more recent data reviewed in this paper.

First, with regard to the Birmingham-Taylor "optimum" operator form $Ke^{-\tau s}$, it appears that some modification may be desirable. There is little question that the required presence of lead terms in the operator transfer characteristic is connected with an increase in the remnant, and hence decreases the tracking precision. Direct evidence on this score is available from the Franklin and Russell data. To some extent, the Goodyear stationary simulator results also corroborate this statement, since on those tests the indifference threshold characteristic was associated with the presence of the lead term in the operator. Based upon these data, then, we can conclude that the "optimum" operator form should contain no lead equalization.

V.2
195

In the general case with finite bandwidth forcing functions, the need to do away with a low frequency operator lag appears questionable. For example, Russell's data showed that the very best performance, in terms of rms tracking error, occurred when a filter having a transfer function of $1/(Ts + 1)$ was inserted after the operator (to smooth the high frequencies of the remnant power), and then a lead-lag of $(Ts + 1)/(Ts + 10)$ prior to the operator to cancel out the lag introduced by the postfilter. The net controlled element transfer function for a $T = 0.5$ second, was $Y_c = \frac{1}{(0.05s + 1)}$. This controlled element transfer characteristic was shown in other tests to be effectively that of a simple tracker. The human transfer characteristic which existed with this controlled element configuration is best approximated by $Y_p = \frac{K_p e^{-\tau s}}{(T_I s + 1)}$, and the mean square error was reduced about a factor of two below that of the simple tracker.[6] In addition to this information, Russell also showed that insertion of a lag in the controlled element characteristic (to "replace" effectively the operator's low frequency lag T_I), with or without a lead in the controlled element, resulted in *more* remnant power (and associated increase in system error) than was the case with $Y_c = 1$. From these data we are led to suggest:

---

[6] The form for Y_p which we have specified is the *simplest* reasonable form. Were we to strive for a more *general*, yet easily used form then we would use either $Y_p = \frac{Ke^{-\tau s}(\alpha T_I s + 1)}{(T_I s + 1)}$ or $Y_p = \frac{Ke^{-\tau s}(\alpha T_I s + 1)}{(T_I s + 1)(T_N s + 1)}$. In most cases the choice is a matter of taste since the data usually allow leeway in their interpretation.

1. A low frequency operator lag term is present and desirable when forcing function exists.
2. The dynamic portion of the over-all controlled element transfer characteristic should appear to the operator, as something between

$$1 \leq Y_c \leq \frac{1}{(0.05s + 1)}. \tag{27}$$

3. The controlled element can be made effective as a filter to attenuate high frequency remnant power. This will probably be most appropriate in those instances where an operator-applied dither signal is an important aspect of the remnant.

The above modifications to the "simple amplifier" preferred form represent relatively minor changes in design procedure. Considerations of forcing function effects on the remnant can result in much more important modifications of the Birmingham-Taylor thesis which was based upon forcing functions which were either non-existent or composed of extremely low frequency components. Consider the modifications imposed by higher frequency forcing functions on the "simple amplifier" design concept for the human:

1. Since best performance occurs for $Y_c \doteq 1$, the Y_p obtaining for this controlled element is to be desired. The preferred operator model should thus be one of the following:

$$Y_p \doteq \frac{Ke^{-\tau_1 s}}{(T_I s + 1)}$$

or

$$Y_p \doteq \frac{Ke^{-\tau s}}{(T_I s + 1)(T_N s + 1)}.$$

2. Since Elkind studied the upper limit of performance for $Y_c = 1$, we can use his findings directly to obtain optimistic measures of the forcing function effects.

We can see from Elkind's data that it is desirable to have as low a bandwidth forcing function as possible (without involving ourselves with boredom or perceptual linearity effects). Further, the rms error expected will be approximately proportional to the square of the effective forcing function bandwidth (see Fig. 7, which recaps some of

Elkind's data on this score). If we would prefer to establish "good" low frequency system response to the forcing function as a criterion, that is, high d-c. gain, we would like to restrict the forcing function bandwidth to a value somewhat less than that equivalent to a rectangular forcing function spectrum cut-off of 0.64 cps. This is based, of course, upon the somewhat arbitrary criterion that a d-c. gain of 15 db or so

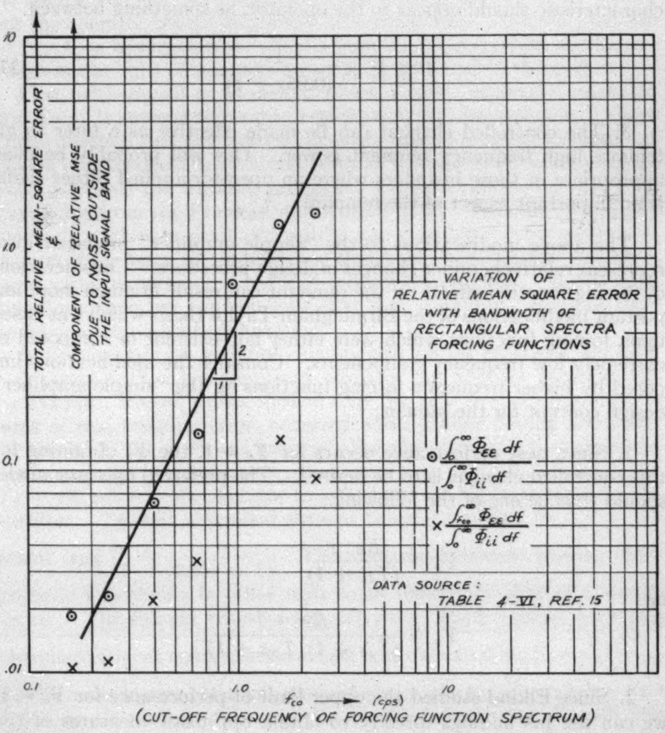

Fig. 7.

yields "good" low frequency response to a system having the over-all open-loop transfer function $Ke^{-\tau s}/(T_I s + 1)$. In any event, by accepting the above modifications to the preferred form, one can use Elkind's data directly to get a firm notion of the best expected system performance.

The design procedure can be summarized as follows:

V.2
195

1. Adjust[7] the low frequency effective controlled element transfer function to that of a simple tracker, that is, within the limits (exclusive of gains):

$$1 \leq Y_c \leq \frac{1}{(0.05s + 1)} \tag{28}$$

a. In this adjustment due care should be taken to filter as much of the operator high frequency remnant power as is possible in the circumstances.

b. The arrangement of equalizing elements, etc., used in modifying the initial controlled element to that of the form above should be such that the operator input bandwidth is as small as practicable.

2. The human transfer characteristic will then be of the approximate form:

$$Y_p \doteq \frac{K_p e^{-\tau s}}{(T_I s + 1)(T_N s + 1)}. \tag{29}$$

a. When the actual system forcing function is put into the form of an "effective" forcing function operating on a simple tracker system (which can be done with the aid of a little block diagram algebra), then the "effective" forcing function spectra can be found. Using Elkind's data as approximations to this forcing function, estimates for K_p and T_I can be made from the forcing function spectral characteristics.

b. The remnant characteristics can also be estimated using either of the remnant models previously fitted to Elkind's data.

3. Using these items of information, the "ideal" system performance can be estimated in detail by normal servo methods. Elkind's rms tracking error data, given in Fig. 7, will also be helpful in this regard. The quantities obtained will always be optimistic since the basic (Elkind) operator data used in the analysis is probably an upper limit of human performance.

While the approach outlined above is intended to represent a rational design procedure for "ideal" systems, it should not be used indiscriminately to design practical systems. However, when used as the basis for an actual system design, two pitfalls should be avoided. The first, and most obvious one, is that of application to areas *beyond* those where the fundamental assumptions used in the derivation of the model are valid. For example, the system should be one where the operator is continuously tracking only visual inputs on his display, and other inputs (including those effectively "set" into the operator by past experience), must be negligible. The second pitfall is commonly encountered in servo practice, and involves the problem of system reliability and over-complication. As an example consider the case of a human pilot-airframe system. The effective controlled element transfer function, that is, the equivalent airframe dynamics, can be put, at least approximately, into the form where $Y_c \doteq 1$. This could be done by judicious design of artificial feel systems, stability augmenters, and compensation of various sorts in a display. The design configuration would presumably be satisfactory (if the first pitfall mentioned is also avoided); and a relatively naive operator could "fly" the aircraft quite well. However, the instant some element of the compensated system fails, the effective controlled element is no longer approximately free of dynamics, and the possible over-all effects could be catastrophic.

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[7] The term "adjustment" as used here means the addition of equalizing devices into the system in such a way as to make the effective controlled element Y_c, as seen by the operator, the form shown above. These equalizing means can consist of series or parallel compensating networks, additional loop closures, etc. These are all straight-forward servo techniques, and need not be discussed here.

To generalize, an "ideal" system established on the basis of the above data can always be used to provide estimates for best possible manual control system performance. In many systems this is its principal value, for when criteria other than tracking performance are important an "ideal" system, in the sense used here, can become an inappropriate physical mechanization. It reduces the role of a human element to one where the human's prime virtue as a control component—adaptability—is essentially suppressed; mechanization can become complex, as noted above; and skill development has little payoff. On the other hand, in instances where the designer can easily avoid complexity, where variability and adaptibility are undesirable, and where naive operators are the norm, the theoretical "ideal" system may be a desirable physical solution as well.

V.2
195

THE FRANKLIN INSTITUTE

MINUTES OF THE STATED MEETING

May 20, 1959

The Stated Meeting of The Franklin Institute was held at 8:15 P.M. in the Lecture Hall. Mr. Wynn Laurence LePage, President, called the meeting to order with approximately 175 members and guests in attendance.

The President stated that the minutes of the Stated Meeting of March 18, 1959 were printed in the April issue of the JOURNAL OF THE FRANKLIN INSTITUTE, and the minutes of the Stated Meeting of April 15, 1959 were printed in the May issue of the JOURNAL OF THE FRANKLIN INSTITUTE. There being no corrections or additions, the minutes of the March 18, 1959 and April 15, 1959 meetings were approved as published.

The President announced that the Board of Managers, at its meeting this afternoon, had nominated the Franklin Medalist for 1959, Professor Hans Albrecht Bethe of Utica, New York, to Honarary Membership in The Franklin Institute, and, in accordance with our By-Laws, his name was presented to the membership for election. On motion duly made and seconded, Professor Bethe was elected an Honorary Member of The Franklin Institute, his membership to be effective October, 1959.

The President recognized Mr. Morton Gibbons-Neff, Chairman of the Membership Committee, who introduced the four members of The Franklin Institute who, in 1959, had completed fifty years of continuous membership. The President then presented a Gold Key and Gold Membership Card to Mr. James McGowan, Jr., Mr. T. Edward Ross, Mr. Theobald F. Clark and Mr. Walton Clark, Sr. (in absentia), asking Mr. Theobald Clark to see that his brother, Walton Clark, received his Gold Key and Gold Membership Card with the sincere appreciation of the Institute for his many years of interest in it.

Mr. Morton Gibbons-Neff then presented the Commandant of the Fourth Naval District, Rear-Admiral Charles H. Lyman, and announced that it is our custom to present membership in The Franklin Institute to the Commandant of the Fourth Naval District. Mr. LePage thereupon said it gave him great pleasure to present to Admiral Lyman his Annual Membership Card, and expressed the hope that he would find it possible to make use of the membership privileges.

Before presenting the speaker of the evening, Mr. LePage called attention to the fact that this evening we would present the Tenth Charles Day Lecture, endowed by Mrs. R. Marshall Truitt in honor of her late husband, Charles Day. Mr. Charles Day was a founder, with the late John E. Zimmerman, of the firm of Day & Zimmerman. He became a member of The Franklin Institute in 1900 and was a member of its Board of Managers from 1908 until his death in 1931.

The President then introduced the speaker of the evening, Dr. Edward B. Doll, Vice President, Space Technology Laboratories, Inc. and Program Director ICBM Atlas.

In his talk on "The Space Market," Dr. Doll discussed the current United States Ballistic Missile program giving technical facts related to ballistic missiles as space vehicles; then, in general terms, the problem of predicting future trends. He commented on the evaluation of the relative values of various space possibilities with observations of desirable educational trends. After the discussion of the United States Ballistic Missile program a most interesting film was shown illustrating progress in this program.

Following an interesting discussion period, the President expressed the Institute's thanks to Dr. Doll and adjourned the meeting at 10:00 P.M.

WILLIAM F. JACKSON, JR.
Secretary

COMMITTEE ON SCIENCE AND THE ARTS

(*Abstract of Proceedings of Stated Meeting held Wednesday, May 13, 1959.*)

HALL OF THE COMMITTEE,
PHILADELPHIA, MAY 13, 1959.

DR. WILLIAM G. SCHMIDT in the Chair.

The following reports were presented for final action:

No. 3197: The Magnetic Fluid Clutch.

This report recommended the award of an Edward Longstreth Medal to Jacob Rabinow, of Takoma Park, Maryland, "In consideration of his invention of the Magnetic Fluid Clutch, a new concept of controlled coupling, of particular importance where smooth slip operation and/or extremely rapid response is essential."

No. 3345: Work of Clarence M. Zener.

This report recommended the award of a John Price Wetherill Medal to Clarence Melvin Zener, of Pittsburgh, Pennsylvania, "In consideration of his important contributions to the field of solid state physics and in particular to the physics of metals; and also of his unusual ability to stimulate important work on the part of others."

No. 3335: The Franklin Medal.

This report recommended the award of The Franklin Medal to Hans Albrecht Bethe, of Ithaca, New York, "For his many profound investigations which have contributed significantly to our understanding of the physical universe from nuclei of atoms to the interior of the stars."

No. 3357:
No. 3358: Ballantine Medal.

The first report recommended the award of a Stuart Ballantine Medal to Charles H. Townes, of New York, New York, "For his conception and demonstration of the feasibility of securing amplification and generation of high frequency radio waves by stimulated emission of radiation and for his invention of the maser which represents a new departure in electronic procedures and which has already led to many fruitful scientific and practical uses."

The second report recommended the award of a Stuart Ballantine Medal to Albert Hoyt Taylor, of Claremont, California, "For his more than fifty years of scientific work, which contributed notable advances in the technology of radio communications, particularly in the fields of radio wave propagation and of reliable communications systems."

D. S. FAHRNEY,
Secretary to Committee

V.2
195

LIBRARY

The Committee on Library desires to add to the collections any technical works that members may wish to contribute. Contributions will be gratefully acknowledged and placed in the Library. Duplicates received will be transferred to other libraries as gifts of the donor. 398 items have been added the past month.

Photostat service. Photostat prints of any material in the collections can be supplied on request.

The Library and reading room are open from 9 A.M. until 5 P.M. on Mondays, Tuesdays, Thursdays, Fridays; from 2 P.M. until 10 P.M. on Wednesdays; and from 9 A.M. until noon on Saturdays.

RECENT ADDITIONS

AERONAUTICS

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V.2
195

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MEMBERSHIP

The following elections were approved on May 7, 1959 by the Membership Committee by authority given to it by the Board of Managers.

ANNUAL

Louis C. Ammlung, Jr.
Harold W. Beswick
Samuel N. Boyd, Jr.
Warren W. Brenner
Charles A. Carr, Jr.
Florence R. Cohen
Robert Edward Craig
Christopher W. Crossett
Lyman A. Darling
Guy DiAmbrosio
Philip J. Diamond
Franklin B. Drumheller
Samuel Enion
Jack Forstadt
Francis E. Hummel, Jr.
T. Peirce Hunter
Alexander Labbok
Roland C. Laney
Alvin S. Levy
A. L. Linch
Herschel N. Livingston
Peter J. Loftus
Harold M. Logan, Jr.
William Linden Long
Paul R. Lutz
James B. Madison
Anthony Maladra
Arthur R. Mandeville
Edward J. Manley
Luther P. Manship
Richard L. Manton
Carlo Mariani, Jr.
John L. Martin
Norman H. Martin
Edmund W. Martindale
John J. Massimiani
Raymond Alan Meyer
T. Elmer Moon
Howard T. O'Neill
Ray L. Overcash
Robert F. Peterson
Charles E. Probst
Helen Pyle
Charles Ritter
Lockhart L. Sands
Eloise Hall Savidge
F. Ralph Sias
Howard L. Smith
Leon E. Smith
John J. Somers
John Peter Stevenson
Leonard M. Strunk
Frank R. Stryke
Benjamin S. Thayer
Charles L. Thomas
Andrew S. Webb
L. W. Wyman

EDUCATOR

Margaret M. Helm
William E. Kelly
Milton Mark
Richard S. Ross
Seymour Schotz
Samuel Sugarman

NON-RESIDENT

William G. Collings
W. Barton Eddison
N. S. Macfarlan

NECROLOGY

John T. Fegley '42
Charles Flachbarth '43
H. J. Levinson '42
S. Weir Newmayer '48
Mrs. Harrison B. Wright '36

V.2
195

BOOK NOTES

HYDRAULIC ENERGY DISSIPATORS, by E. A. Elevatorski. 214 pages, illustrations, 6 × 9 in. New York, McGraw-Hill Book Co., Inc., 1959. Price, $10.00.

This book gives a thorough presentation of the theoretical and practical aspects of hydraulic energy dissipators. Written especially for the designer of hydraulic structures, the various functions and uses of energy dissipators are clearly described and illustrated. Design procedures for such elements as hydraulic jump type stilling basins, valves and gates, bucket-type energy dissipators and drop structure stilling basins are topics thoroughly examined. Design examples and problems dealt with are: preventive measures for erosion below existing dams; use of hydraulic models and model-prototype conformance.

267
59

THE CELLULAR SLIME MOLDS, by John Tyler Bonner. 150 pages, diagrams, plates, 5½ × 8½ in. Princeton, Princeton University Press, 1959. Price, $4.00.

In this volume the author discusses the relation of cellular slime molds to other organisms and the structure and life histories of various types of slime molds. Briefly summarizing the work already done in this field, the book's emphasis is placed on the mechanics of development and attempts to fit the knowledge of slime molds into modern embryological views. A comprehensive bibliography is included and should prove a valuable reference for specialists as well as a useful introduction for the non-specialist.

BASIC PHYSICS OF ATOMS AND MOLECULES, by U. Fano and L. Fano. 414 pages, diagrams, 6 × 9 in. New York, John Wiley & Sons, Inc., 1959. Price, $10.00.

This volume presents a qualitative picture of the properties of atoms rather than the detailed techniques of quantum mechanical calculations. The authors give a clear, unified presentation of quantum physics, without requiring an extensive previous knowledge of physical theory or familiarity with its mathematical procedures. The inductive analysis starts from a few experiments that illustrate directly the characteristic properties of atomic systems.

NUCLEONICS FUNDAMENTALS, by David B. Hoisington. 410 pages, illustrations, 6 × 9 in. New York, McGraw-Hill Book Co., Inc., 1959. Price, $9.50.

Offering a broad survey of the field of nuclear physics and engineering, this book deals with the accomplishments, applications, problems and limitations associated with the use of radioactive substances, nuclear reactors and other nuclear devices of science and industry. Some of the topics discussed are basic atomic and nuclear physics, particle accelerators, radiation protection, instrumentation, fission, reactor principles, research and power reactors, thermonuclear power, nuclear explosives and isotope separation. Treatment of the subject matter is not highly mathematical, with the differential notation used sparingly. A text for students whose mathematical training has been limited to algebra and slight knowledge of calculus.

MODERN TRANSISTOR CIRCUITS, by John M. Carroll. 268 pages, illustrations, 8½ × 11 in. New York, McGraw-Hill Book Co., Inc., 1959. Price, $8.50.

A comprehensive collection of modern transistor circuits, classified and arranged for easy reference, is presented in this volume. Almost 200 circuits are presented, with complete design information and electronic component values. The circuits are arranged both by generic types such as amplifiers, oscillators, power supplies and pulse circuits as well as by specialized applications such as broadcast and home entertainment; audio and r-f communications circuits. Emphasis is given to new circuits combining transistors and electron tubes, and transistors and magnetic amplifiers. Profusely illustrated with schematic diagrams, and photographs showing construction of equipment.

LIQUID SCINTILLATION COUNTING, edited by Carlos G. Bell, Jr. and F. Newton Hayes. 292 pages, diagrams, plates, 6 × 9 in. New York, Pergamon Press, Inc., 1958. Price, $10.00.

This is the first volume ever published on this technique of radiation measurement. It covers all the advances in the field and includes a section on the chemistry of the counting sample. With scintillation counters being one of the most versatile and important instruments in modern nuclear research, this informative text on the subject will prove to be of immense value to nuclear physicists, physical chemists, electronic engineers, radio chemists and those engaged in medical research.

ELECTRICAL ENGINEERING MATERIALS, by A. J. Dekker. 208 pages, diagrams, 6 × 9 in. New York, Prentice-Hall, Inc., 1959. Price, $8.00.

In this new text, the author gives a clear, working knowledge of the methods and models used to determine the properties of materials most important to the electrical engineer. Simple classical or semi-classical models are used throughout to help the reader develop insight into the physical mechanisms that underlie the properties of materials. The chapers are organized so that concentration is possible separately on the dielectric, magnetic or conductive properties of materials. Supplemented with numerous line drawings, as well as graphs and tables, the book also incorporates problems at the end of each chapter.

THE THEORY AND DESIGN OF MAGNETIC AMPLIFIERS, by E. H. Forest-Smith. 487 pages, diagrams, 5½ × 8¼ in. New York, John Wiley & Sons, Inc., 1959. Price, $12.50.

This volume is the first of a series on Automation and Control Engineering. It gives an account of the theory of magnetic amplifiers and design methods to meet specific requirements which should prove valuable to the control engineer. In the various chapters, theoretical aspects are supplemented by short numerical examples and some complete designs are carried out. Some typical problems to which magnetic amplifiers have been applied successfully are also discussed.

MAGNETIC AMPLIFIER ENGINEERING, by George M. Attura. 220 pages, diagrams, illustrations, 6 × 9 in. New York, McGraw-Hill Book Co., Inc., 1959. Price, $7.50.

This authoritative guide, presented in the language of the electronic circuit and systems engineer, presents the theory, operating principles and practical application of all types of magnetic amplifiers. Basic information is given on electric and magnetic variables describing their interrelation through the equations of Faraday and Oersted. Special topics not covered before in a work of this kind include: hybrid circuits, bi-directional output amplifier, volt-second analysis of saturable reactors, winding and test specifications for toroidal reactors and detailed mathematical analysis of the load action of the reactor-rectifier amplifier.

V.26
195

PUBLICATIONS RECEIVED

MECHANICAL DESIGN AND ANALYSIS, by R. R. Slaymaker. 418 pages, illustrations, 6 × 9 in. New York, John Wiley & Sons, Inc., 1959. Price, $9.50.

A DICTIONARY OF NAMED EFFECTS AND LAWS, in chemistry, physics and mathematics, by D. W. G. Ballentyne and L. E. Q. Walker. 205 pages, diagrams, 5½ × 8½ in. New York, The Macmillan Company, 1959. Price, $6.00.

THE DESIGN OF PHYSICS RESEARCH LABORATORIES, a symposium. 108 pages, diagrams, illustrations, 6 × 9¼ in. New York, Reinhold Publishing Corp., 1959. Price, $4.50.

MATHEMATICS DICTIONARY, edited by Glenn James and Robert C. James. Second edition, 546 pages, diagrams, 6 × 9 in. Princeton, D. Van Nostrand Co., Inc., 1959. Price, $15.00.

ENGINEERING MECHANICS, STATICS AND DYNAMICS, by H. L. Langhaar and A. P. Boresi. 705 pages, diagrams, 6 × 9 in. New York, McGraw-Hill Book Co., Inc., 1959. Price, $9.00.

PRINCIPLES OF MODERN PHYSICS, by Robert B. Leighton. 795 pages, diagrams, 6 × 9 in. New York, McGraw-Hill Book Co., 1959. Price, $7.50.

GRAPHICAL COMMUNICATION, by Earl D. Black. 328 pages, diagrams, 6 × 9 in. New York, McGraw-Hill Book Co., 1959. Price, $8.00.

EVERYDAY METEOROLOGY, by A. Austin Miller and M. Parry. 270 pages, diagrams, illustrations, 6 × 9 in. New York, Philosophical Library, 1959. Price, $7.50.

COUNTERPOINT, by L. Virginia Holland. 128 pages, 5½ × 8½ in. New York, Philosophical Library, 1959. Price, $3.75.

ELECTRICAL SAFETY, by H. W. Swann. 292 pages, illustrations, 5½ × 8½ in. New York, Philosophical Library, 1959. Price, $15.00.

CLASSICAL MECHANICS, by J. W. Leech. 149 pages, diagrams, 7¼ × 4¼ in. New York, John Wiley & Sons, Inc., 1959. Price, $2.50.

APPLIED MATHEMATICS FOR ENGINEERS AND SCIENTISTS, by C. G. Lambe. 518 pages, diagrams, 5½ × 8½ in. New York, The Macmillan Company, 1959. Price, $8.50.

THE FOURIER INTEGRAL AND CERTAIN OF ITS APPLICATIONS, by Norbert Wiener. 201 pages, 5½ × 8 in. New York, Dover Publications, Inc., 1959. Price, $1.50 (paper).

THE GENTLE ART OF MATHEMATICS, by Dan Pedoe. 143 pages, diagrams, 8½ × 5½ in. New York, The Macmillan Company, 1959. Price, $3.50.

INTRODUCTION TO STRESS ANALYSIS, by Charles O. Harris. 330 pages, diagrams, 6 × 9¼ in. New York, The Macmillan Company, 1959. Price, $7.50.

HELICOPTERS AND AUTOGYROS OF THE WORLD, by Paul Lambermont with Anthony Pirie. 255 pages, plates, 5½ × 8½ in. New York, Philosophical Library, 1959. Price, $10.00.

PROFESSIONAL CREATIVITY, by Eugene Von Fange. 260 pages, diagrams, 8½ × 5½ in. New York, Prentice-Hall, Inc., 1959. Price, $4.95.

CURRENT TOPICS

Small Component Motor Design.—A Unitized motor, representing a major technological breakthrough in small component motor design, that is up to 40 per cent more efficient than conventional motors of the same type, has been developed by the General Electric Company.

Available first in 4-pole, KSM 59-frame, shaded-pole and permanent-split capacitor ratings up through 1/15 hp, the new motor is designed for use in such air moving and small machine applications as ventilators, heaters, dehumidifiers, air conditioners, coolers, recorders, projectors, business machines and in many other types of small motor-driven equipment.

Also to be available soon will be Unitized motors in 2-pole, shaded-pole ratings through 20 milli-horsepower and universal series motors of various ratings. A complete line of the new motors will become available as designs are developed, according to engineers at the company's Specialty Motor Department, Fort Wayne, Ind.

Smaller in size for a given output than motors of traditional design, the Unitized motor will offer the original equipment manufacturer a number of options based upon his motor-driven equipment requirements. Relative to conventional motor design, the new design offers either higher output for the same size, input, and temperature rise; or lower current input for the same size, output, and temperature rise; or lower temperature rise for the same size, input, and output.

New developments in the bearings, the lubrication system, and the insulation contribute to the over-all life and performance characteristics of the motor. The flexible Unitized motor design can be adapted easily to specific needs of a variety of small motor-driven products.

A continuous hydrodynamic oil film supports the motor shaft in all of the new sleeve-bearing Unitized motors. A capillary retention system prevents excess loss of oil from the lubrication system.

Bearings on the new Unitized motors are permanently aligned in the manufacturing process and are rigidly supported by the end shields. The bearings hold the rotor centered in the stator even against side loading, thus permitting the motor to be mounted in any position.

A specially developed resin, which has high mechanical and dielectric strength, coats the entire stator core. Core laminations are then fused into a complete and integrated unit. Tests indicate that the new stator core insulation is not affected by humidity. These test results also indicated that it has a four-to-one improvement in dielectric strength and a projected life 10 times that of conventional paper-slot insulation, company engineers said.

The new Unitized motor design can be adapted easily to specific needs of products in the small motor-driven equipment field. Because they can be mounted in any position, Unitized motors can meet many special requirements without factory modification.

A variety of mounting arrangements, shaft extensions, and lead materials and connections can be accommodated by the new motor. Enclosed and open designs are available and special enclosures can be provided where necessary.

V.2
195

Semiconductor Tetrode.—A new four terminal semiconductor device, which will perform a number of electronic functions which previously either could not be obtained at all, or only with extensive circuitry, has recently been invented at Bell Telephone Laboratories.

The device, the field effect tetrode, can be made to function as a transformer, gyrator, isolator, non-distorting modulator, or a short-circuit stable negative resistance. Laboratory models have been produced by the inventors, H. A. Stone, Jr., and R. M. Warner, Jr., which corroborate the theoretical predictions for operation of the device. This theory grew out of work previously reported on a field effect current limiter.

The tetrode is composed of a disk of semiconductor with a diffused junction. A circular trench is cut and etched into each face of the disk, to within about 1 mil of the junction on either side. Two leads are then attached to each face, one inside the trench, the other outside. When a voltage is applied across the junction, the thickness of the depletion layer adjacent to it is increased or decreased, depending on the direction of the biasing voltage. This in turn increases or decreases the resistance of each "channel" between the bottom of the trench and the junction.

Functionally, the device has no analog, either in electron tubes or in previous transistors. The tetrode will function either as a transformer or a gyrator, depending on the polarity of the biasing voltage. As a transformer, it has a very decided size advantage for low frequency use, although it does not afford d-c isolation. As a gyrator, it should be of considerable circuit interest. (A gyrator is a non-reciprocal four terminal network which behaves similarly to a transformer, while exhibiting a 180° difference in phase shift depending on the direction of transmission.) One gyrator function is impedance inversion. For example, it should be possible to use the new device to convert the reactance of a miniature capacitor into that of a high-Q inductor.

If the device is biased properly, it will function as an isolator, allowing passage of alternating current in one direction only.

According to its inventors, one of the most important applications for the new device may be as a distortionless modulator, or electronically controlled resistor for large signals. In this use, a relatively low frequency control-voltage varies the width of the depletion layer, and thus the resistance of the device. Simple capacitors act as high-pass filters to isolate the control-voltage from the signal, if the frequency ratio is maintained at a high level. The signal voltage does not appear across the junction and has no effect on the depletion layer. Therefore, it can be magnitudes higher than the control voltage, without being distorted by self-modulation. For the same reason, it is not limited by junction capacitance.

If a direct connection is made between the inner lead on one face and the outer lead on the other, the device will function as a two terminal a-c short-circuit stable negative resistance. In the experimental models produced at Bell Laboratories, this performance has been achieved over a range of about 30 to 250 v, at 0.6 to 0.1 ma, in a boron-doped silicon crystal with a phosphorous diffused junction.

While the practical development of the field effect tetrode is still in a very early stage, nevertheless, it shows potential characteristics in a single device which previously either could not be obtained at all, or only through extensive circuitry.

New Method for Studying Shock Waves in Metals.—An accurate and easy method of measuring and recording transient elastic waves created in metals by impacts and explosions has been developed at the U. S. Army Engineer Research and Development Laboratories, Fort Belvoir, Va.

Simple in comparison with complicated and undependable methods attempted in the past, the new system gives research engineers a means of studying the patterns of shock waves and their speed of transmission in solid materials in order to establish design criteria to minimize the effects of explosive shock on military equipment.

In operation, an explosion set off at one end of a metal bar to which a strain gage has been attached, sends a shock wave down the bar at tremendous speed. The strain gage picks off a reading from the shock wave and transmits a signal to amplifiers. These, in turn, display a reading on the calibrated face of an oscilloscope in the form of a pip of light. A Polaroid camera with shutter opened is prefocused on the face of the oscilloscope and records the pip in the form of a line as it passes. The curve of the pip of light indicates the speed of propagation of the shock wave, maximum strain, shape and changes of the wave, and duration of strains. The oscilloscope is set for a 4-microsecond sweep to reproduce a detailed display of the signal picked up by the strain gage.

This test method as designed and developed by Mr. Allan Tarr in collaboration with Privates W. E. Bron and K. A. Zadwick of the Engineer Labs' Materials Branch is expected to enable engineers to predict more accurately the effects of a given force such as explosions or bullets on finished equipment.

Electric Movie Camera.—The Baskon Electric Eight, a revolutionary electric-driven 8-mm movie camera with an electric eye to eliminate the need for exposure meters, an electric voltmeter to indicate when batteries are wearing out and a three lens turret, has been announced by Robert C. Baggott, vice president of marketing for Baskon Corporation, Beverly Hills, Calif.

An unique "footage counter" built into the view finder is another feature of the camera. Explaining Baskon's unique "footage counter" in the view finder, Baggott said it enables the photographer to know at all times how much film has been used, thereby preventing him from running out of film at crucial moments.

"Merely pressing a button puts the Baskon into motion—there's no winding, another advantage in action photography," Baggott added. The camera provides a continuous run of over 1000 feet of film.

Ordinary pen-lite batteries, easily available, power the Baskon, and its electric voltmeter tells when to replace them.

The camera's three lenses, which all stop down to $f/1.8$, are standard, 13mm; wide angle, 6.5mm; and telephoto, 25mm. Each lens enables an exact field of view, which changes to match the lens being used as the turret is revolved.

Beacon Light Pathfinder for Assembling Airborne Troops.—Army Engineers at Fort Belvoir, Va., have developed a lightweight, air-droppable pathfinder beacon light developed to mark assembly points for airborne troops. The beacon light has an infrared range of 2 miles when viewed from the ground and a visible light range of 5 miles when viewed from 1000-ft. altitude.

V.2
195

The light is mounted on a telescoping mast which can be extended to 23 ft. Six signal lenses are provided in white, red, amber, green, blue and infrared. A coding mechanism permits a pre-coded sequence of four Morse Code characters, manually or automatically, key coded or a continuously lighted beacon.

The beacon mast is reduced to 30 in. in the carrying case which also contains a 12-volt rechargeable nickel cadmium battery and the coding sequence mechanism. Total weight of the case and components is 20 lb.

The pathfinder can be erected and operated by one man. Developed by the U. S. Army Engineer Research and Development Laboratories, Fort Belvoir, Virginia, it is now undergoing user tests at Fort Bragg, North Carolina.

Long-Lasting Atomic Lamps.—Bulbs powered by radioactivity may be ready for the commercial market before long. One well-known British lighting company has manufactured atomic lamps and is conducting extensive experiments to test their practical applications. An atomic lamp—powered entirely by radioactivity—is expected to shine many years without attention or renewal of the atomic power source.

Until recently there was no practical light source that would run for long periods without external supplies. But radio isotopes changed that. Radioactive substances, particularly gaseous isotopes such as tritium and krypton 85, are suitable for use in light sources, and the A.E.I. Lamp & Lighting Co. (London) has been experimenting with both. The light is obtained from phosphorus activated by beta particles which are emitted in the course of the decay process of the radioactive gas.

These experimental atomic lamps have an output of 0.0045 lumens, which represent an efficiency of just over 30 lumens per watt. While they are not bright enough to be used for illumination, they are suitable as indicator lamps. Lamps with a lens diameter of 3 in. have been made which are visible in the dark at about a quarter of a mile. If the present brightness could be increased by a factor of ten, a considerable range of applications could be found. For instance, the lamps could be used as warning lights on obstructions, for markers on buoys or for short-range signaling on liferafts.

The first lamp experimented on consisted of a glass bulb coated on the inside with phosphor and filled with radioactive gas. But more recent models have an area of clear glass—a window to allow the light from the phosphor to escape with as little loss as possible. The bulb is of hard glass and the phosphor mixed with a suitable binder is introduced into the bulb through a short neck and then allowed to drain. When the binder has dried, the window is formed by scraping away the phosphor. The bulb is then baked to remove the binder, leaving only the phosphor on the wall of the bulb. Finally, a glass tube is joined to the neck of the bulb, and through this it is filled with radioactive gas and then sealed.

It is claimed that a source of a few cubic centimeters in volume is completely safe in operation and would be a negligible health hazard in case of breakage.

Capacity of Floating Zone Refiners Increased.—A striking improvement in the floating zone refining technique, substantially increasing the volume of material which can be purified, has been made by W. G. Pfann, K. E. Benson, and D. W. Hagelbarger of Bell Telephone Laboratories. Paradoxically, the new technique also makes it possible to treat much thinner cross sections than have been feasible before.

The floating zone technique has proven highly valuable in producing extreme purity in reactive metals and semiconductors, because the molten material is never in contact with a container. However, it has been limited until now to use with small amounts of material.

In conventional floating zone refining, a rod of the material to be purified is held in a vertical position, while a zone is melted by a heat source. The molten zone is held in place within the rod by its own surface tension. This zone is then made to move along the rod, and the impurities which collect in the molten material move to one end. The end is subsequently cut off, before the material is fabricated into devices.

The primary limitation on the conventional method is the fact that for any given material, there is a maximum height of molten zone which can be supported by the surface tension. Small diameter rods can be melted through easily without exceeding this maximum height. However, in larger diameters, by the time the rod has been melted through, the height of the zone has become so great that the surface tension can no longer hold the volume of molten material.

The new method gets around this difficulty by using specially shaped cross sections, such as flat plates and tubes. These shapes provide a cross section small in thickness to permit melting through without exceeding the maximum height, and large in width to increase the total cross-sectional area treated. The inventors have shown that molten zones in such shapes are surprisingly stable.

For example, it is almost impossible to produce a stable molten zone in a one-inch diameter iron rod, because the maximum height of the zone is generally exceeded during the heating required to melt through the rod. However, it is relatively easy to melt the entire cross section of a two-inch diameter, $\frac{1}{8}$-in. wall tube of the same material, without exceeding this maximum height. The areas in both forms are the same.

Stable, wide molten zones have been maintained experimentally in one or both cross-sectional shapes, in materials such as silicon, iron, tin, gold, lead, bismuth, and water.

The new method works well at very small plate thicknesses in contrast to the rod floating zone method, in which the maximum stable zone height decreases to zero as the rod diameter decreases. Such a decrease in maximum zone height can be avoided in the new method. Hence, treatment of sheets in the order of mils or less in thickness becomes feasible.

It is expected that increases in cross-sectional areas at least five to ten times those currently used will be feasible. Also, this new wide zone technique should make the floating zone method applicable to materials for which the conventional method is not practical. It appears that this new technique will greatly enhance the utility of the floating zone principle in the purification of reactive materials.

Both the original zone refining technique and the floating zone extension of the method were discovered at Bell Laboratories, by W. G. Pfann and H. C. Theuerer, respectively.

Telemetering Transmitter for Space Satellites.—An all-transistor 20-megacycle telemetering transmitter, designed for possible use in space satellites, has been built by Philco Corporation for the U. S. Army. This is the first U. S. satellite transmitter to

V.2
195

operate in the 20-mc band and it has the same type of modulation used by standard radio stations and amateur radio operators. Also, it has more power output and is more efficient than the transistorized transmitters used in present U. S. satellites. Developed by Philco's Research division for the Army Ordnance Missile Command, the satellite transmitter weighs less than 10 ounces, is 5 in. in diameter and 1 in. high.

New Philco high frequency power transistors made it possible to build this telemetering transmitter which provides up to one watt of output power. This is in contrast to one-to-two hundredths of a watt of output from transistorized transmitters in present U. S. satellites.

These power transistors, developed especially for the 20-mc transmitter by Philco's Lansdale Tube division, are used instead of bulky vacuum tubes which require large batteries of short life span.

Another transistor advantage is that nearly one half of the power taken from a satellite's batteries, which operate the transmitter, is radiated as radio frequency energy. This is an important advancement since electrical power is limited and precious in an orbiting space satellite.

The Philco satellite transmitter is capable of operating at high efficiency in outer space within a temperature range of 5 to 187 F.

Industrial Stereo-Microscope with Low Power Attachment.—Increasingly important in quality control, production line inspection, research work and small parts assembly is a new industrial stereo-microscope with low power attachment now being manufactured by Edmund Scientific Company.

Because it provides three-dimensional vision, the Edmund Stereo-Microscope permits the detection of flaws in materials, reveals depth of depressions in surfaces and makes it far easier to interpret images under magnification. Erect image allows production workers to use only normal movements while working on magnified operations. Low power and wider fields of view with depth permit industrial applications impossible with conventional microscopes. Current uses include: checking of air seals on cans, analysis of oil well cores, examination of textile samples, inspection of work turned out by machine tools, close work on engravings and printed matter.

The Edmund Stereo-Microscope is unusually rugged for hard, industrial use. Base is cast iron and body aluminum, finely machined on bearing surfaces. Features include: two sets of objectives on rotating turret for a variety of powers, standard range of interpupilary adjustment, helical rack and pinion focusing—3-in. smooth travel, clear bright image, wide field optics, achromatic objectives and eye lenses, long working distance of 2 and 3 in. long overhand for examining bulky objects. Additional eye-pieces and low power adjustment (special lens mounted on rod which fastens to arm of microscope) give a power of 6, 10, 23 and 40. The instrument is fully tested, adjusted and guaranteed.

INDEX TO VOLUME 267

January–June, 1959

SUBJECT INDEX

Entries with (C) indicate Current Topics. Papers are listed under subject headings, with authors' names in parentheses following the title of the paper. Authors are listed, with titles of their papers, in alphabetical order in the Author Index, but not in the Subject Index.

A

Absorption spectra. Predicting absorption spectra for composite solutions (Bolie), 143
Accelerometers. Cathode follower probe improves accelerometer performance, 260(C)
Adaptive controls. A class of optimum control systems (Merriam), 267
Airplanes. Flight test equipment for jet airliners, 185(C)
Aitchison, Robert B. Wetherill Medal, 169
Alloys. Weldable alloy for highly stressed parts, 134(C)
All-pass networks. Constant-resistance all-pass networks with maximally flat time delay (Weinberg), 35
Annual Report of the Board of Managers for the year 1958, 317
Annulus. An elastoplastic analysis of a rotating annulus (Owen), 55
Architecture. New design for school laboratories, 263(C)
Astronomy. Satellite observatories, 98(C)
  Television for stratoscope balloon flights, 94(C)
  Television system for high altitude solar observation, 262(C)
Atomic energy. Atom blast simulator tests materials, 184(C)
Atomic physics. Motion pictures of dislocations in graphite, 100(C)
  Single atomic particle photographed, 361(C)
Automatic control. A unified approach to the theory of sampling systems (Kalman and Bertram), 405
Automation. Automatic library, 185(C)
  Oscar Fisher Company unveil new automatic X-ray processor, 265(C)
  Tiny logic circuit elements, 510(C)

B

Ballantine Medal
  Albert Hoyt Taylor, 538
  Charles H. Townes, 538
Ballistics. Exploding guns aid missile development, 54(C)
Balloons. Television for stratoscope balloon flights, 94(C)
  Television system for high altitude solar observation, 262(C)
Beacon light pathfinder for assembling airborne troops, 548(C)
Bethe, Hans, Albrecht. Franklin Medal, 538
Bioengineering. Simple electronic circuit simulates living nerve cell, 404(C)
Bonding. New developments in thermocompression bonding, 97(C)
Book reviews
  Abramson, H. Norman: An introduction to the dynamics of airplanes, 86
  Ahrens, L. H., Frank Press, Kalervo Rankama and S. K. Runcorn: Physics and chemistry of the earth, vol. II, 84
  Aseltine, John A.: Transform method in linear system analysis, 89
  Attura, George M.: Magnetic amplifier engineering, 544
  Bailey, G. L. J., T. P. Hoar, F. T. Barwell and R. W. B. Stephens: Effect of surface on the behaviour of metals, 89
  Baines, H.: The science of photography, 179
  Balabanian, Norman: Network synthesis, 175
  Barnes, H.: Oceanography and marine biology, 458
  Barnett, Orville T.: Filler metals for joining, 458
  Beedle, Lynn S.: Plastic design of steel frames, 355

267
59

Book reviews (*cont.*)
  Bell, Carlos G., Jr. and F. Newton Hayes, ed.: Liquid scintillation counting, 544
  Bendat, Julius S.: Principles and applications of random noise theory, 454
  Benioff, Hugo, Maurice Ewing, B. J. Howell, Jr. and Frank Press: Contributions in geophysics. Volume I on earth sciences, 89
  Bergaust, Erik and Seabrook Hull: Rocket to the moon, 175
  Bernhardt, Robert C., ed.: Processing of thermoplastic materials, 354
  Bers, Lipman: Mathematical aspects of subsonic and transonic gas dynamics, 353
  Bethe, H. A. and E. E. Salpeter: Quantum mechanics of one- and two- electron atoms, 174
  Bok, Bart J.: The astronomer's universe, 457
  Bonner, John Tyler: The cellular slime molds, 543
  Boyd, John, ed.: Lubrication science and technology, 459
  Bunshah, R. F.: Vacuum metallurgy, 254
  Caldwell, Samuel H.: Switching circuits and logical design, 83
  Cambel, Ali Bulent and Burgess H. Jennings: Gas dynamics, 86
  Campbell, Donald P.: Process dynamics, 351
  Carroll, John M.: Modern transistor circuits, 543
  Casey, Robert S., James W. Perry, Allen Kent and Madeline Berry: Punched cards, 91
  Cauer, Wilhelm: Synthesis of linear communication networks, vols. I and II, 178
  Chorafas, Dimitris N.: Operations research for industrial management, 180
  Crandall, Stephen H., ed.: Random vibration, 456
  Dapples, Edward C.: Basic geology for science and engineering, 460
  Dekker, A. J.: Electrical engineering materials, 544
  di Venedetto, Giovanni: Bibliografia marconiana, 90
  Diels, K. and R. Jaeckel: Leybold vakuumtaschbuch, 356
  Duffin, D. J.: Laminated plastics, 358
  Dungey, J. W.: Cosmic electrodynamics, 456
  Elevatorski, E. A.: Hydraulic energy dissipators, 543
  Elliott, John F.: The physical chemistry of steelmaking, 180
  Fano, U. and L. Fano: Basic physics of atoms and molecules, 543
  Feinstein, Amiel: Foundations of information theory, 179
  Fischer, Heinz and Lawrence C. Mansur: Conference on extremely high temperatures, 176
  Fleming, Richard, ed.: Scale-up in practice, 357
  Forest-Smith, E. H.: The theory and design of magnetic amplifiers, 544
  Forsythe, George E. and Paul C. Rosenbloom: Numerical analysis and partial differential equations, 353
  Friedlander, F. G.: Sound pulses, 351
  Galbraith, W.: Extensive air showers, 354
  Gibson, A. F., P. Aigrain and R. E. Burgess: Progress in semiconductors, vol. 3, 88
  Godfrey, J. W. and G. Parr, ed.: The technical writer, 457
  Goodier, J. N. and P. G. Hodge, Jr.: Elasticity and plasticity, 353
  Guy, Albert G.: Elements of physical metallurgy, 458
  Hála, Eduard, Jiří Pick, Vojtěch Fried and Otakar Vilím: Vapour-liquid equilibrium, 355
  Hale, Arthur J.: The interference microscope in biological research, 90
  Hamilton, J. J.: Reflex klystrons, 457
  Hanson, N. R.: Patterns of discovery, 91
  Heiskanen, W. A. and F. A. Vening Meinesz: The earth and its gravity field, 354
  Hintenberger, H.: Nuclear masses and their determination, 85
  Hix, C. F., Jr. and R. P. Alley: Physical laws and effects, 461
  Hodge, Philip G., Jr.: Plastic analysis of structures, 460
  Hohn, Franz E.: Elementary matrix algebra, 178
  Hoisington, David B.: Nucleonics fundamentals, 543
  Iwinski, T.: Theory of beams, 356
  Jackson, J. D.: The physics of elementary particles, 181
  Jacobsen, Lydik and Robert S. Ayre: Engineering vibrations, 454
  Kaplansky, Irving, Marshall Hall, Jr., Edwin Hewitt and Robert Fortet: Some aspects of analysis and probability, 353

Book reviews (*cont.*)
  Karplus, Walter J.: Analog simulation, 90
  Kays, W. M. and A. L. London: Compact heat exchangers, 180
  Ku, Y. H.: Analysis and control of nonlinear systems, 254
  Landsberg, H. E. and J. Mieghem: Advances in geophysics, vol. 5, 88
  Lansdell, Norman: The atom and the energy revolution, 459
  Leimanis, E. and N. Minorsky: Dynamics and nonlinear mechanics, 353
  Mandl, Matthew: Fundamentals of Digital Computers, 179
  McCormick, Ernest J.: Human engineering, 453
  Melman, Seymour: Decision-making and productivity, 357
  Metzger, Robert W.: Elementary mathematical programming, 178
  Milne, Lorus J. and Margery Milne: Animal life, 458
  Nestorides, E. J.: Handbook on torsional vibrations, 174
  Neumann, J. Alex: Welding of plastics, 459
  O'Flaherty, Fred, William T. Roddy and Robert M. Lollar, ed.: The chemistry and technology of leather, vol. 2, types of tannages, 354
  Orr, Clyde, Jr. and J. M. Dalla Valle: Fine particle measurement, 457
  Platt, Sidney: Magnetic amplifiers: theory and application, 90
  Present, R. D.: Kinetic theory of gases, 90
  Ragazzini, John R. and Gene F. Franklin: Sampled-data control systems, 89
  Read, John, Clifford Paine, John Gwynant Evans and Sir Alexander Todd: Perkin centenary London. 100 years of synthetic dyestuffs, 179
  Roberts, Richard B.: Microcosmal particles and protein synthesis, 179
  Robin, Louis: Fonctions sphériques de Legendre et fonctions sphéroidales, tome 2, 356
  Rough, Frank A. and Arthur A. Bauer: Constitutional diagrams of uranium and thorium alloys, 458
  Saaty, Thomas L.: Mathematical methods of operations research, 459
  Sadler, Walter C.: Legal aspects of construction, 461
  Sandretto, Peter C.: Electronic avigation engineering, 352
  Sarton, George: A history of science, 456
  Schieldrop, Edgar B.: The air, 181
  Scientific manpower in Europe, 358
  Scorer, R. S.: Natural aerodynamics, 85
  Segrè, E.: Annual review of nuclear science, vol. 8, 180
  Seitz, F. and D. Turnbull: Solid state physics, vol. 7, 255
  Semenov, N. N.: Some problems of chemical kinetics and reactivity, 453
  Shy, G. M., R. B. Bradley and W. B. Matthews, Jr.: External collimation detection of intracranial neoplasia with unstable nuclides, 357
  Skeist, Irving: Epoxy resins, 88
  Taylor, E. Openshaw: Nuclear reactors for power generation, 178
  Thirring, Walter E.: Principles of quantum electrodynamics, 180
  Thompson, M. S.: Gum plastics (rubber-modified plastics), 88
  Von Mises, Richard: Mathematical theory of compressible fluid flow, 253
  Warren, Francis A.: Rocket propellants, 256
  Watson, Jane Werner: The world of science, 90
  Whyburn, Gordon T.: Topological analysis, 355
  Wiener, Norbert: Nonlinear problems in random theory, 355
  Wolfendale, E.: The junction transistor, 89
Bounded stream. Oblique impact of a bounded stream on a plane lamina (Sarpkaya), 229
Brainpower. The neglected capital (Steele), 295
Brazing. Ultrasonic brazing, 183(C)
Broadcasting. New stereophonic radio system, 24(C)
  Stereo sound broadcasting now compatible with single channel reception, 466(C)
Brown Medal. Hardy Cross, 169

C

Cables. TASI will double the capacity of submarine telephone cables, 464(C)
Cameras. Electric movie camera, 548(C)
Catalysts. Spherical kaolin catalyst, 94(C)
Cells. Simple electronic circuit simulates living nerve cell, 404(C)
Ceramics. New material, Avcoite, for structural use above 5000 F., 282(C)

V.2
195

Chemistry. Predicting absorption spectra for composite solutions (Bolie), 143
  Total synthesis of yohimbine, 95(C)
Chinese. The Sinotype—a machine for the composition of Chinese from a keyboard (Caldwell), 471
Cinephotomicrography. Etch patterns in zinc (Damiano and Herman), 303
Circuits. Tiny logic circuit elements, 510(C)
  Topological evaluation of network functions (Kim), 283
Clothing. Durable pleating and creasing process for wool, 463(C)
  Washable wool suits, 54(C)
Coding systems. New error-correction code for bursts of errors, 468(C)
Color television. Microscope color TV system, 465(C)
Colorimetry. Predicting absorption spectra for composite solutions (Bolie), 143
Committee on Science and the Arts
  Abstracts of meetings: December 10, 1958, 71; January 14, 1959, 169; March 11, 1959, 345; April 8, 1959, 438; May 13, 1959, 538
  Awards (*See* Ballantine Medal, Brown Medal, Cresson Medal, Franklin Medal, Longstreth Medal, Potts Medal, Wetherill Medal, in main index)
Communications. Automatic library, 185(C)
  New error-correction code for bursts of errors, 468(C)
  Satellite "post office" system proposed, 182(C)
Computers. Tiny logic circuit elements, 510(C)
Constant-resistance networks. Constant-resistance all-pass networks with maximally flat time delay (Weinberg), 35
Control. A class of optimum control systems (Merriam), 267
  Liquid flywheel to control space craft, 96(C)
Cookers. Solar cookers for underprivileged, 467(C)
Creep. A creep analysis of rotating solid disks (Ma), 149
Cresson Medal
  Henry Charles Harrison, 345
  John Hays Hammond, Jr., 438
  Irving Wolff, 71
Cross, Hardy. Brown Medal, 169
Crystallography. Etch patterns in zinc (Damiano and Herman), 303
  Ferroelectric polarization reversal in barium titanate, 261(C)
  New powder pattern technique, 258(C)

D

Data processing. Automatic library, 185(C)
Data recovery. "Messenger" from outer space, 100(C)
Deformation. A creep analysis of rotating solid disks (Ma), 149
  The influence of gravity on the folding of a layered viscoelastic medium under compression (Biot), 211
Dielectrics. On explanations of electric and magnetic constants and units (Gresky), 201
  Ferroelectric polarization reversal in barium titanate, 261(C)
Dimensional analysis. On explanations of electric and magnetic constants and units (Gresky), 201
Discrete data systems. A unified approach to the theory of sampling systems (Kalman and Bertram), 405
Dislocations. Etch patterns in zinc (Damiano and Herman), 303
  Motion pictures of discolations in graphite, 100(C)
Domain structure. New powder pattern technique, 258(C)
Dynamic systems. A unified approach to the theory of sampling systems (Kalman and Bertram), 405

E

Earth satellites. Satellite "post office" system proposed, 182(C)
Education. The neglected capital (Steele, 295
  New design for school laboratories, 263(C)
Elastoplastic analysis of a rotating annulus (Owen), 55
Electrical networks. Topological evaluation of network functions (Kim), 283
Electromagnetic theory. On explanations of electric and magnetic constants and units (Gresky), 201
Electromechanics. Acoustic noise generator tests rocket components, 142(C)
Electron properties. On explanations of electric and magnetic constants and units (Gresky), 201

Electron tubes. Ultrascope, new aid to medical and industrial research, 316(C)

Electronics. Semiconductor tetrode, 547(C)
  Simple electronic circuit simulates living nerve cell, 404(C)

Electrons. Single atomic particle photographed, 361(C)

Elliptic functions. A reduced solution for the simple pendulum: new approach to elliptic functions (Gold), 503

Engineering psychology. The human operator as a servo system element (McRuer and Krendel), 381, 511

Error detection. New error-correction code for bursts of errors, 468(C)

Etch patterns in zinc (Damiano and Herman), 303

Expeditions. The international (geophysical) years—an appraisal (Gerson), 135

F

Faraday effects. The ionospheric Faraday effect and its applications (Daniels and Bauer), 187

Feedback control. A class of optimum control systems (Merriam), 267

Field effect tetrode. Semiconductor tetrode, 547(C)

Fire protection. Electric-powered firefighting vehicle, 134(C)

Floating zone refining. Capacity of floating zone refiners increased, 549(C)

Fluid flow. A Green's function solution for the case of laminar incompressible flow between non-concentric circular cylinders (Heyda), 25

Fluxless brazing. Ultrasonic brazing, 183(C)

Folding. The influence of gravity on the folding of a layered viscoelastic medium under compression (Biot), 211

The Franklin Institute
  Annual Report of the Board of Managers for the year 1958, 317
  Committee on Science and the Arts (*See* Committee on Science and the Arts in main index)
  The Franklin Institute Laboratories (*See* Franklin Institute Laboratories in main index)
  Journal of The Franklin Institute (*See* Journal of The Franklin Institute in main index)
  Library (*See* Library of The Franklin Institute in main index)
  Meetings (*See* Meetings of The Franklin Institute in main index)
  Membership (*See* Members of The Franklin Institute in main index)

Franklin Institute Laboratories
  Check list of publications, 75
  Thermoelectric energy conversion in solids (Fuschillo), 443

Franklin Medal. Hans Albrecht Bethe, 538

Free trade. The neglected capital (Steele), 295

G

Generalized specific heats. Some thermodynamic properties of a mapping (Christie), 119

Geophysics. The international (geophysical) years—an appraisal (Gerson), 135

Germanium. Acoustoelectric effect in germanium, 260(C)

Graphic arts. The Sinotype—a machine for the composition of Chinese from a keyboard (Caldwell), 471

Graphite. Motion pictures of dislocations in graphite, 100(C)

Gravity. The influence of gravity on the folding of a layered viscoelastic medium under compression (Biot), 211

Green's Function. A Green's function solution for the case of laminar incompressible flow between non-concentric circular cylinders (Heyda), 25

Guided missiles. Subminiature emitter-follower, 94(C)

H

Hammond, John Hays, Jr. Cresson Medal, 438

High temperature. Auto-optic recording pyrometer, 464(C)
  New material, Avcoite, for structural use above 5000 F., 282(C)

High vacuum techniques. Cryopumping, 97(C)

Hypersonics. Exploding guns aid missile development, 54(C)

Hypervelocity instrumentation aids ICBM nose cone design, 294(C)

I

Illumination. Long-lasting atomic lamps, 549(C)

Impact. New method for studying shock waves in metals, 548(C)

V.2
195

Impact (*cont.*)
  Oblique impact of a bounded stream on a plane lamina (Sarpkaya), 229
Incompressible flow. A Green's function solution for the case of laminar incompressible flow between non-concentric circular cylinders (Heyda), 25
Industry. The neglected capital (Steele), 295
  Ultrascope, new aid to medical and industrial research, 316(C)
Inspection. Industrial stereo-microscope with low power attachment, 551(C)
Instruments. Auto-optic recording pyrometer, 464(C)
  Cathode follower probe improves accelerometer performance, 260(C)
  Hypervelocity instrumentation aids ICBM nose design, 294(C)
  In-circuit transistor tester, 260(C)
  Industrial stereo-microscope with low power attachment, 551(C)
  Liquid flywheel to control space craft, 96(C)
  Magnetometer for space-exploring rockets, 184(C)
  Moisture balance with built-in autotransformer, 259(C)
  New tension meter, 96(C)
  Subminiature emitter-follower, 94(C)
  Wall-mounted tensile tester, 166(C)
International geophysical year. The international (geophysical) years—an appraisal (Gerson), 135
Inverse series analysis. A reduced solution for the simple pendulum: new approach to elliptic functions (Gold), 503
Ionospheric physics. The ionospheric Faraday effect and its applications (Daniels and Bauer), 187
Isometric sphere method. Theory of noisy two-port networks (Bolinder), 1

J

James, A. T. Wetherill Medal, 345
Jet planes. Flight test equipment for jet airliners, 185(C)
Joffe method. Theory of the A. F. Joffe method for rapid measurement of the thermal conductivity of solids (Swann), 363
Journal of The Franklin Institute
  Publications received: 87, 177, 257, 359, 462, 545

L

Laboratory equipment. New design for School laboratories, 263(C)
Laminar incompressible flow. A Green's function solution for the case of laminar incompressible flow between non-concentric circular cylinders (Heyda), 25
Lamps. Long-lasting atomic lamps, 549(C)
Language. The Sinotype—a machine for the composition of Chinese from a keyboard (Caldwell), 471
Lattice networks. Constant-resistance all-pass networks with maximally flat time delay (Weinberg), 35
Lenses. New TV lens, 264 (C)
Libraries. Automatic library, 185(C)
Library of The Franklin Institute
  Recent additions: 72, 169, 248, 345, 440, 539
Linear graph theory. Topological evaluation of network functions (Kim), 283
Logic circuits. Tiny logic circuit elements, 510(C)
Longstreth Medal. Jacob Rabinow, 538
Low temperature. Cryopumping, 97(C)

M

Magnetic permeability. On explanations of electric and magnetic constants and units (Gresky), 201
Magnets. Giant magnets in industry, 360(C)
Mail. Satellite "post office" system proposed, 182(C)
Maintenance. Giant magnets in industry, 360(C)
Manned flight. The technology of manned return from outer space (Paige), 103
Manpower. The neglected capital (Steele), 295
Mapping. Some thermodynamic properties of a mapping (Christie), 119
Martin, A. J. P. Wetherill Medal, 345
Mathematics. A reduced solution for the simple pendulum: new approach to elliptic functions (Gold), 503
Measurement. The international yard and pound, 470(C)
  New method for studying shock waves in metals, 548(C)
  New tension meter, 96(C)
  Theory of the A. F. Joffe method for rapid measurement of the thermal conductivity of solids (Swann), 364

Medical science. Microscope color TV system, 465(C)
  Oscar Fisher Company unveil new automatic x-ray processor, 265(C)
  Simple electronic circuit simulates living nerve cell, 404(C)
Meetings of The Franklin Institute
  Minutes: December 17, 1958, 69; January 21, 1959, 167; February 18, 1959, 243; March 18, 1959, 344; April 15, 1959, 437; May 20, 1959, 537
Members of The Franklin Institute
  Gold members for 1958 honored, 70
  New members: 71, 173, 245, 350, 439, 542
  Silver members for 1958 honored, 244
Metallurgy. Capacity of floating zone refiners increased, 549(C)
  Etch patterns in zinc (Damiano and Herman), 303
  New method for studying shock waves in metals, 548(C)
Microscopy. Industrial stereo-microscope with low power attachment, 551(C)
  Microscope color TV system, 465(C)
  Ultrascope, new aid to medical aid industrial research, 316(C)
Military engineering. Beacon light pathfinder for assembling airborne troops, 548(C)
  Electric-powered firefighting vehicle, 134(C)
  Unique shelter for use with Jupiter missile, 463(C)
Miniaturization. Small component motor design, 546(C)
  Tiny logic circuit elements, 510(C)
Missiles. Ammonium perchlorate plant, 93(C)
  Cryopumping, 97(C)
  Exploding guns aid missile development, 54(C)
  Hypervelocity instrumentation aids ICBM nose cone design, 294(C)
  "Messenger" from outer space, 100(C)
  New material, Avcoite, for structural use above 5000 F., 282(C)
  Unique shelter for use with Jupiter missile, 463(C)
Morey, George W. Potts Medal, 345
Motion pictures. Electric movie camera, 548(C)
Motors. Small component motor design, 546(C)

N

Network synthesis. Constant-resistance all-pass networks with maximally flat time delay (Weinberg), 35
Network theory. Theory of noisy two-port networks (Bolinder), 1
  Topological evaluation of network functions (Kim), 283
Noise. New error-correction code for bursts of errors, 468(C)
  Theory of noisy two-port networks. (Bolinder), 1
Non-concentric annulus. A Green's function solution for the case of laminar incompressible flow between non-concentric circular cylinders (Heyda), 25
Non-homogeneous fluids. The influence of gravity on the folding of a layered visco-elastic medium under compression (Biot), 211
Nose cones. Hypervelocity instrumentation aids ICBM nose cone design, 294(C)
  The technology of manned return from outer space (Paige), 103
Nuclear physics. Single atomic particle photographed, 361(C)
Nuclear power. Radar space observatory, 360(C)

O

Oblique impact. Oblique impact of a bounded stream on a plane lamina (Sarpkaya), 229
Oil refining. Spherical kaolin catalyst, 94(C)
Optics. Auto-optic recording pyrometer, 464(C)
  Beacon light pathfinder for assembling airborne troops, 548(C)
  New TV lens, 264(C)
Optimization. A class of optimum control systems (Merriam), 267
Oscillation. A reduced solution for the simple pendulum: new approach to elliptic functions (Gold), 503

P

Pendulum. A reduced solution for the simple pendulum: new approach to elliptic functions (Gold), 503
Perturbation method. An elastoplastic analysis of a rotating annulus (Owen), 55
Photography. Electric movie camera, 548(C)
  Single atomic particle photographed, 361(C)

V.2
195

Piezoelectricity. New powder pattern technique, 258(C)
Plane lamina. Oblique impact of a bounded stream on a plane lamina (Sarpkaya), 229
Plasticity. An elastroplastic analysis of a rotating annulus (Owen), 55
Pleating. Durable pleating and creasing process for wool, 463(C)
Poisson's equation. A Green's function solution for the case of laminar incompressible flow between non-concentric cirular cylinders (Heyda), 25
Polar years. The international (geophysical) years—an appraisal (Gerson), 135
Potts Medal. George W. Morey, 345
Powder patterns. New powder pattern technique, 258(C)
Power sources. Radar space observatory, 360(C)
Printing. The Sinotype—a machine for the composition of Chinese from a keyboard (Caldwell), 471
Probes. British telescope followed "Pioneer," 92(C)
  "Messenger" from outer space, 100(C)
Projective geometry. Some thermodynamic properties of a mapping (Christie), 119
Propellants. Ammonium perchlorate plant, 93(C)
  Ion rocket engine, 166(C)
Protective coatings. Resisteg coating, 282(C)
Pumps. Electric-powered firefighting vehicle, 134(C)
Pyrometers. Auto-optic recording pyrometer, 464(C)

Q

Quality control. Industrial stereo-microscope with low power attachment, 551(C)
Quasi-linear processes. The human operator as a servo system element (McRuer and Krendel), 381, 511

R

Rabinow, Jacob. Longstreth Medal, 538
Radar. The ionospheric Faraday effect and its applications (Daniels and Bauer), 187
  Radar space observatory, 360(C)
Radiation pressure. Solar sails, 92(C)
Radio. New stereophonic radio system, 24(C)
  Stereo sound broadcasting now compatible with single channel reception, 466(C)
Radio telescopes. British telescope followed "Pioneer," 92(C)
Radioactivity. Long-lasting atomic lamps, 549(C)
Redding Lecture. The technology of manned return from outer space (Paige), 103
Re-entry. The technology of manned return from outer space (Paige), 103
Resistors. Resisteg coating, 282(C)
Rheology. The influence of gravity on the folding of a layered viscoelastic medium under compression (Biot), 211
Rockets. Acoustic noise generator tests rocket components, 142(C)
  Magnetometer for space-exploring rockets, 184(C)
  Ion rocket engine, 166(C)
  New material, Avcoite, for structural use above 5000 F., 282(C)
  Satellite "post office" system proposed, 182(C)
Rotating disks. A creep analysis of rotating, solid disks (Ma), 149
  An elastoplastic analysis of a rotating annulus (Owen), 55
Royal Institution. The proceedings of the Royal Institution of Great Britain, 259(C)

S

Sampled-data systems. A unified approach to the theory of sampling systems (Kalman and Bertram), 405
Satellites. The ionospheric Faraday effect and its applications (Daniels and Bauer), 187
  Satellite observatories, 98(C)
  Satellite "post office" system proposed, 182(C)
  Subminiature emitter-follower, 94(C)
  Telemetering transmitter for space satellites, 550(C)
Scintillation. Single atomic particle photographed, 361(C)
Semiconductors. Acoustoelectric effect in germanium, 260(C)
  Capacity of floating zone refiners increased, 549(C)
  New developments in thermocompression bonding, 97(C)
  Semiconductor tetrode, 547(C)

Semiconductors (*cont.*)
Theory of the A. F. Joffe method for rapid measurement of the thermal conductivity of solids (Swann), 363
Servomechanisms. The human operator as a servo system element (McRuer and Krendel), 381, 511
A unified approach to the theory of sampling systems (Kalman and Bertram), 405
Shear. A creep analysis of rotating solid disks (Ma), 149
Shelters. Unique shelter for use with Jupiter missile, 463(C)
Shock. Hypervelocity instrumentation aids ICBM nose cone design, 294(C)
New method for studying shock waves in metals, 548(C)
Sinotype—a machine for the composition of Chinese from a keyboard (Caldwell), 471
Sociology. Solar cookers for underprivileged, 467(C)
Solar energy. Solar cookers for underprivileged, 467(C)
Solar observation. Television system for high altitude solar observation, 262(C)
Solar satellites. Satellite observatories, 98(C)
Solid state physics. Sound waves of 10,000 megacycles, 362(C)
Theory of the A. F. Joffe method for rapid measurement of the thermal conductivity of solids (Swann), 363
Sound. Sound waves of 10,000 megacycles, 362(C)
Space technology. Magnetometer for space-exploring rockets, 184(C)
"Messenger" from outer space, 100(C)
Radar space observatory, 360(C)
The technology of manned return from outer space (Paige), 103
Telemetering transmitter for space satellites, 550(C)
Space travel. Liquid flywheel to control space craft, 96(C)
Solar sails, 92(C)
Spectrophotometry. Predicting absorption spectra for composite solutions (Bolie), 143
Stability. The influence of gravity on the folding of a layered viscoelastic medium under compression (Biot), 211
Standardization. The international yard and pound, 470(C)
Static. New error-correction code for bursts of errors, 468(C)
Steel. Weldable alloy for highly stressed parts, 134(C)
Stereophonic sound. New stereophonic radio system, 24(C)
Stereo sound broadcasting now compatible with single channel reception, 466(C)
Stochastic processes. The human operator as a servo system element (McRuer and Krendel), 381, 511
Streamline theory. Oblique impact of a bounded stream on a plane lamina (Sarpkaya), 229
Stress. A creep analysis of rotating solid disks (Ma), 149
An elastoplastic analysis of a rotating annulus (Owen), 55
Synge, R. L. M. Wetherill Medal, 345
Synthesis. Constant-resistance all-pass networks with maximally flat time delay (Weinberg), 35
Total synthesis of yohimbine, 95(C)
System analysis. A unified approach to the theory of sampling systems (Kalman and Bertram), 405
System design. A class of optimum control systems (Merriam), 267
Systems engineering. The human operator as a servo system element (McRuer and Krendel), 381, 511

T

Taylor, Albert Hoyt Ballantine Medal, 538
Technical literature. The Proceedings of the Royal Institution of Great Britain, 259(C)
Telemetry. Flight test equipment for jet airliners, 185(C)
Telemetering transmitter for space satellites, 550(C)
Telephony. TASI will double the capacity of submarine telephone cables, 464(C)
Telescopes. British telescope followed "Pioneer," 92(C)
Television for stratoscope balloon flights, 94(C)
Television. Microscope color TV system, 465(C)
New TV lens, 264(C)

V.26
195

Television (*cont.*)
  Stereo sound broadcasting now compatible with single channel reception, 466(C)
  Television for stratoscope balloon flights, 94(C)
  Television system for high altitude solar observation, 262(C)
Tensiometers. New tension meter, 96(C)
Tension. Wall-mounted tensile tester, 166(C)
Testing. Acoustic noise generator tests rocket components, 142(C)
  Atom blast simulator tests materials, 184(C)
  Flight test equipment for jet airliners, 185(C)
  In-circuit transistor tester, 260(C)
  Wall-mounted tensile tester, 166(C)
Tetrodes. Semiconductor tetrode, 547(C)
Textiles. Durable pleating and creasing process for wool, 463(C)
  Washable wool suits, 54(C)
Theoretical chemistry. Predicting absorption spectra for composite solutions (Bolie), 143
Theory of the A. F. Joffe method for rapid measurement of the thermal conductivity of solids (Swann), 363
Thermal conductivity. Theory of the A. F. Joffe method for rapid measurement of the thermal conductivity of solids (Swann), 363
Thermocompression bonding. New developments in thermocompression bonding, 97(C)
Thermodynamics. Some thermodynamic properties of a mapping (Christie), 119
Time delay networks. Constant-resistance all-pass networks with maximally flat time delay (Weinberg), 35
Time-domain. A class of optimum control systems (Merriam), 267
Topology. Some thermodynamic properties of a mapping (Christie), 119
  Topological evaluation of network functions (Kim), 283
Townes, Chalres H. Ballantine Medal, 538
Tracking. British telescope followed "Pioneer," 92(C)
  Subminiature emitter-follower, 94(C)
Transistors. In-circuit transistor tester, 260(C)
  Microscope color TV system, 465(C)
  TASI will double the capacity of submarine telephone cables, 464(C)
  Telemetering transmitter for space satellites, 550(C)
  Theory of noisy two-port networks (Bolinder), 1
Transmission. TASI will double the capacity of submarine telephone cables, 464(C)
Tresca's yield criterion. An elastoplastic analysis of a rotating annulus (Owen), 55
Two-port networks. Theory of noisy two-port networks (Bolinder), 1
Typesetting. The Sinotype—a machine for the composition of Chinese from a keyboard (Caldwell), 471

U

Ultrasonics. Sound waves of 10,000 megacycles, 362(C)
  Ultrasonic brazing, 183(C)
Universal constants. On explanations of electric and magnetic constants and units (Gresky), 201

V

Vibration. Sound waves of 10,000 megacycles, 362(C)
Viscoelasticity. The influence of gravity on the folding of a layered viscoelastic medium under compression (Biot), 211

W

Wave propagation. The ionospheric Faraday effect and its applications (Daniels and Bauer), 187
Welding. Weldable alloy for highly stressed parts, 134(C)
Wetherill Medal
  Robert B. Aitchison, 169
  A. T. James, 345
  A. J. P. Martin, 345
  R. L. M. Synge, 345
  Clarence Melvin Zener, 538
Wind tunnels. Cryopumping, 97(C)
Wire. Resisteg coating, 282(C)
Wolff, Irving. Cresson Medal, 71
Wool. Durable pleating and creasing process for wool, 463(C)
  Washable wool suits, 54(C)

X

X-rays. Oscar Fisher Company unveil new automatic X-ray processor, 265(C)

Y

Yohimbine. Total synthesis of yohimbine, 95(C)

Z

Zener, Clarence Melvin. Wetherill Medal, 538

Zinc. Etch patterns in zinc (Damiano and Herman), 303

Zone refining. Capacity of floating zone refiners increased, 549(C)

Zoom lenses. New TV lens, 264(C)

AUTHOR INDEX

Full titles of papers are listed only under first authors; all co-authors are cross-referenced to the full entry. Entries with (FIL) indicate Franklin Institute Laboratories contributions.

Bauer, Siefgried J.: *See* Daniels, Fred B. and Siegfried J. Bauer, 187

Bertram, J. E.: *See* Kalman, R. E. and J. E. Bertram, 405

Biot, M. A.: The influence of gravity on the folding of a layered viscoelastic medium under compression, 211

Bolie, Victor W.: Predicting absorption spectra for composite solutions, 143

Bolinder, E. Folke: Theory of noisy two-port networks, 1

Caldwell, Samuel H.: The Sinotype—a machine for the composition of Chinese from a keyboard, 471

Christie, Dan E.: Some thermodynamic properties of a mapping, 119

Damiano, Victor V. and Marvin Herman: Etch patterns in zinc, 303

Daniels, Fred B. and Siegfried J. Bauer; The ionospheric Faraday effect and its applications, 187

Fuschillo, Nicholas: Thermoelectric energy conversion in solids (FIL), 443

Gerson, N. C.: The international (geophysical) years—an appraisal, 135

Gold, Louis: A reduced solution for the simple pendulum: new approach to elliptic functions, 503

Gresky, A. T.: On explanations of electric and magnetic constants and units, 201

Herman, Marvin: *See* Damiano, Victor V. and Marvin Herman, 303

Heyda, James D.: A Green's function solution for the case of laminar incompressible flow between non-concentric circular cylinders, 25

Kalman, R. E. and J. E. Bertram: A unified approach to the theory of sampling systems, 405

Kim, Wan Hee: Topological evaluation of network functions, 283

Krendel, Ezra S.: *See* McRuer, Duane T. and Ezra S. Krendel, 381, 511

Ma, B. M.: A creep analysis of rotating solid disks, 149

McRuer, Duane T. and Ezra S. Krendel: The human operator as a servo system element, 381, 511

Merriam, C. W., III: A class of optimum control systems, 267

Owen, M. J.: An elastroplastic analysis of a rotating annulus, 55

Paige, Hilliard W.: The technology of manned return from outer space, 103

Sarpkaya, Turgut: Oblique impact of a bounded stream on a plane lamina, 229

Steele, Sydney: The neglected capital, 295

Swann, W. F. G.: Theory of the A. F. Joffe method for rapid measurement of the thermal conductivity of solids, 363

Weinberg, Louis: Constant-resistance all-pass networks with maximally flat time delay, 35

V.2
195